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16. ABSTRACT

The Federal Aviation Administration's air traffic control organization (ATO) encompasses a variety of facilities that include towers, terminal radar approach control facilities (TRACONs), and air route traffic control centers (ARTCCs). Well trained air traffic controllers using effective automation can exploit alarms, alerts and warnings (collectively, signals) to build situation awareness and to reduce cognitive workload. We have written the first version of a handbook that will guide air traffic system designers and controller user teams as they collaborate with human factors experts to create or modify air traffic control system alarms, alerts, and warnings. The handbook describes a novel signal framework that can be used to evaluate an existing ATC signal or design a new signal using an objective scoring sheet and a structured interview format with subject matter experts (*i.e.*, air traffic controllers) during the design process. This framework provides relevant personnel with a common language that allows them to describe, classify, and objectively evaluate signals in air traffic control. The signal framework and its associated structured interview will be tested and validated with air traffic controllers during Phase 4. Phase 5 of the project will include further refinement of the signaling handbook as necessary and the development of training materials. At the conclusion of this project, the Air Traffic Organization will have the tools necessary to develop signals that will help to keep the United States' National Airspace System the safest in the world.

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A Handbook for Signal Design:
Alarms, Alerts, and Warnings in Air Traffic Control

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This is the preliminary draft of a signal design handbook and is the deliverable for the third year of a five-year project. This interim version is for informational purposes only. The guidance contained in this handbook will be validated during the next two phases of the project and may be changed during the validation studies. Only the final version of the handbook should therefore be used to guide signal design.

Executive Summary

An air traffic control (ATC) facility is a dynamic, high-stress environment that requires that controllers rapidly detect problems and make time-critical decisions. Signals (alarms, alerts, and warnings) are essential for alerting controllers to potential collisions and other adverse events, but they can increase operators' response times and decrease their response rates (so-called *alarm fatigue*). As the first step in creating a handbook guiding the design and use of ATC signals, we have developed a signaling design philosophy that can enhance the effectiveness of signals in the ATC environment. (Ruskin *et al*., 2021) This information can be used to develop strategies that can enhance signaling modalities (*e.g.*, new auditory, visual, and tactile signals) and guide the ways that these signals are used. We determined that signals can be divided into four categories that require increasing levels of intervention by the controller:

- Priority 1: Immediate danger requiring urgent controller intervention. (*e.g,* Imminent near mid-air collision [NMAC], flight below MVA, AMASS)
- Priority 2: Risk of harm. Controller intervention will be required soon (*e.g.*, Predicted conflict, airspace alert)
- Priority 3: Informational. Intervention may be required (*e.g.*, Mode C intruder)
- Priority 4 or diagnostic (*e.g.*, Radar outage, localizer malfunction)

There are also opportunities to improve controllers' trust in automated ATC systems in the setting of the many signals that these automated systems produce. Trust in automation may be also improved by through enhancements in the automation itself. For example, the equipment display could indicate the level of confidence the automation places in the hazard actually occurring, such as when notifying the controller of an impending loss of separation.

Our signaling philosophy addresses these four priority levels for notifying the controller of important operational events, as well as considerations for varying operating environmental conditions, from the darkened radar room to the bright daytime illumination in the ATC tower cab environment. For example, indicator lights and messages on screens may be less noticeable when displayed in a brightly illuminated control tower environment. In the tower cab, the increased use of auditory signals and modifications to displays that enhance the visibility of

screens and lights may be beneficial. Tactile displays (i.e., those using the sense of touch) might also be used to draw a controller's attention to an urgent condition. Improving the localizability of auditory signals may help controllers diagnose a problem more quickly. The simultaneous use of signals for multiple sensory modalities might be valuable when controller response time is critical. Voice alerts for extremely high-priority alarms indicating potential loss of life has been shown to reduce response time in domains outside of aviation. New classes of auditory signals, including *earcons* and *spearcons*, may help controllers differentiate between different conditions and the urgency of a hazard. Making signals more acoustically rich and explicitly encoding intended urgency can clarify intent. Signals should be easily distinguishable from each other and should use features such as color, text, and acoustic features to increase their saliency and informativeness. We will describe specific strategies for improving alarm performance with these features. This signaling philosophy forms the basis of specific recommendations contained in this handbook. Although the signal design techniques described in this handbook were developed for air traffic control systems, they may have broad applicability across multiple domains.

Human Factors

The design of signals should support the controllers' primary task of traffic separation as well as supplementary tasks. Signals should also support the early recognition and mitigation of hazards such as traffic conflicts without imposing additional workload caused by nuisance signals. Signal design based on the principles of human factors can help to ensure that new and existing signals help controllers to maintain the safety of the National Airspace System. The "high-level" design and review principles contained in the human performance section of our handbook represent the overarching characteristics that will maximize the utility of signals in air traffic control.

Signal Design Process

Our signal design handbook includes a comprehensive framework that guides subject matter experts, human factors experts, and equipment designers who must work as a team to identify each operational situation that requires a signal for the controller (such as a specific hazard, for example) and create signal that should be associated with it. It is intended to provide designers, engineers, human factors experts, subject matter experts, and vendors with a common language to describe, classify, and objectively evaluate and design signals in air traffic control, with potential applications in related domains. The framework allows signal developers to perform objective scoring and structured interviews to assess signal efficacy using 15 properties in five categories: HOW, WHAT, WHERE, WHEN, and WHAT. It can be used to evaluate an existing ATC signal or design a new signal using an objective scoring sheet and a structured interview format with subject matter experts (i.e., air traffic controllers). Although this handbook will not contain a comprehensive review of equipment design, the principles that we have outlined can be used to support the creation and evaluation of new and existing signals.

Presented in five chapters and containing two appendices, the handbook provides a signal design method along with the supporting human factors literature and conceptual framework on which it was founded. The appendices include a step-by-step approach and an initial list of those candidate operational situations for which new or modified signals would be most appropriate for the earliest consideration.

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Chapter 1: Introduction

The United States Federal Aviation Administration's air traffic organization (ATO) encompasses a variety of Air Traffic Control (ATC) facilities that include towers, terminal radar approach control facilities (TRACONs), and air route traffic control centers (ARTCCs). ATC facilities are dynamic, high-stress environments in which controllers are required to make quick decisions and rapid interventions. Controllers routinely interact with pilots of varying skill levels, aircraft with different capabilities, and flights at dissimilar speeds, altitudes, and trajectories. Each of these factors add to the controller's task complexity. Additional complexity arises from the various automated warnings and alerts that are designed to gain the controller's attention and inform the controller of potentially high-consequence situations and events (*e.g.*, Conflict Alert, Minimum Safe Altitude Warning, inflight emergency, and lost communications (No Radio or NORDO alert). In this chapter, we present a comprehensive review of how operational events and automated ATC signaling systems affect controllers. Our goal is to document the ways in which reliable and unreliable signals contribute to the complexity of their associated tasks. In later chapters, we will describe a new signal framework that facilitates the development of improved alarms, alerts, and warnings in air traffic control. This framework can be used to develop new signals and improve existing signals and could also be considered for inclusion in future versions of the FAA's Human Factors Design Standards.

Similarities between Air Traffic Control and Anesthesia

Although air traffic control and the practice of anesthesiology are different domains, they are similar in their use of automation to manage safety-critical events in a fast-paced, dynamic environment. Like air traffic control, the practice of anesthesiology is dynamic, tightly coupled, and driven by critical events. Anesthesiologists routinely use highly automated, advanced medical technology to perform a variety of tasks, including drug delivery, patient monitoring, and respiratory support (Ruskin et al., 2020). Anesthesiologists continually observe multiple devices that display patient information while performing other tasks such as administering fluids and medications, completing the medical record, and operating various pieces of equipment. Caring for patients in this environment combines intermittent high-workload periods with prolonged vigilance, planning proactively for possible critical events. In addition to watching their physiologic monitors, anesthesiologists rely on specific cues to warn them of an impending critical event. These cues may be a change in the pitch of an oxygen monitor, an audible alarm, or even the conversation between the surgeons or other care team members. In other words, anesthesia is a vigilance task in which the physicians rely on alarms, alerts, and warnings to alert them to safety critical events, much like air traffic control. Our team has studied the role of automation and alarms in patient care, and our experience in the medical domain provides a useful starting point for signal design in air traffic control. (Ruskin and Hueske-Kraus, 2015)

Signals

The term *signal* describes a sensory stimulus that serves the general function of notifying a human operator of a situation that might require their intervention (*i.e.*, an alarm, alert, or warning). Signals can convey a continuum of information that may range from alerting a controller to a situation that requires no action to an emergency in which the controller must act immediately to prevent harm or loss of life. To meet this requirement, effective signals are designed to be intrusive to attract the operator's attention and lead to an intervention. Bliss, Gilson, and Deaton (1995) have proposed a taxonomy of signals that is based upon the timing between a signal and its associated hazard. According to Bliss *et al*., an *alarm* is defined as a transient sensory signal (usually auditory or visual) that indicates the presence of an ongoing danger that requires immediate corrective action. An *alert* indicates that an adverse event may occur sometime soon, usually soon enough for the operator to remember the alert. While alarms and alerts are temporary dynamic signals triggered by a changing situation, a *warning* is usually a permanent visual indication of a static and unchanging hazard. Although this taxonomy has not been adopted for the signals currently used by air traffic controllers, the 2016 Human Factors Design Standard (HFDS), Section 5.5.1, offers recommendations for signals under the generic terms of *Alarms and Alerts*. For example, Bliss and Gilson would define the Minimum Safe Altitude Warning (MSAW) or the Conflict Alert (CA) as *alarms*. The ERAM Conflict Probe (a steady visual indicator that may be activated up to 20 minutes prior to an event for aircraft loss of separation and 40 minutes prior to a potential airspace violation) would be defined as an *alert*. NOTAMs indicating a runway closure or restricted airspace would be defined as a *warning*.

Air traffic controllers rely upon accurate, timely, and reliable signals to maintain safety within the National Airspace System (NAS). However, they experience nuisance signals that may impair performance. One study estimated that 62% of Conflict Alerts (CAs) and 91% of Minimum Safe Altitude Warnings (MSAWs) in the en route environment, and 44% of CAs and 61% of MSAWs in the terminal environment, did not require intervention by a controller (Friedman-Berg and Allendoerfer, 2008). In a study of the effects of imperfect automation on air traffic controllers, Rovira and Parasuraman (2010) found that both false alarms and misses had adverse effects on performance. Controllers' responses to signals may also vary based on the situation. Controllers may act independently of a signal for some conditions or delay acting on other conditions until more information is available. For example, controllers often consider a MSAW to be more urgent than a CA and may therefore respond to an MSAW more quickly (Allendoerfer, Pai, and Friedman-Berg, 2008). Finally, operators experience a *resumption lag* after being interrupted by a signal, time that a controller requires to gather his or her thoughts and resume their previous task (Altmann & Trafton, 2002).

Signals that are perceived to be overly unreliable can provoke the so-called "cry-wolf effect," in which an operator either disables or deprioritizes the alarm (Breznitz, 1984). This effect can be especially problematic during periods of high workload when the operator does not have time to assess the aid's reliability and chooses instead to abandon it (Bliss and Dunn, 2000; Rice, 2009). The cry-wolf effect has been noted before and raises concerns about the effectiveness of alarms with poor reliability (Wickens, Rice, Keller, Hutchins, Hughes, and Clayton, 2009). A meta-analysis by Rein *et al* (2013) concluded that increased reliability was associated with improved performance, with greater than 67% reliability improving performance over baseline reliability. This finding was similar to a previous meta-analysis by Wickens and Dixon (2007). The authors concluded this study with a caution that they could not determine a baseline level of acceptable reliability for alarms in all domains and that performance requirements should be determined by the specific task environment.

Operator experience and understanding related to signals can impact signal effectiveness. Operator behavior in response to signals can be divided into *reliance* (complete trust that no signal means that no intervention is needed) and *compliance* (always responding to a signal with a designated action) (Meyer, 2001). Signal errors can affect this interaction. Bliss (2001; 2004) initially found that excessive false alarms reduce compliance while excessive misses reduce reliance; however, Dixon and Wickens (2006), Dixon, Wickens and MacCarley (2007), and Rice (2009) showed that both type of errors affect both reliance and compliance. The alarm's actual function may not be the same as the user's perception of that function, which may also degrade trust. A controller may perceive a correctly presented CA to be a false alarm when two aircraft established on converging RNP approaches to parallel runways are approaching head-on yet adequate separation will be preserved if they remain on their respective published flight paths. The operator must therefore understand a signal's intended function and set thresholds if the signal is to be effective.

According to Signal Detection Theory (Green and Swets, 1967), a signal can be a *hit* (true positive), a *correct rejection* (true negative), a *false alarm* (false positive), or a *miss* (false negative) (Stanislaw, 1999). In the ATC environment, false alarms can be further divided into a true *false alarm* (a signal is generated even though the threshold has not been exceeded) and a *nuisance alarm* (a signal is generated correctly based on exceedance of a threshold, but at a point where no response is needed). A controller may have already recognized the situation and planned an action to correct it but the alarm is activated because the automation has not yet detected the controller's response (Wickens *et al*., 2009). ATC surveillance systems do not currently allow a controller to indicate that he or she has detected a potential problem and taken action to prevent it, allowing the system to suppress the relevant signal while monitoring the situation in the background. For example, a Minimum Safe Altitude Warning (MSAW) may activate when an aircraft has a high descent rate, even if the pilot plans to level off at a safe altitude. Aircraft on curved approaches to parallel runways may follow flight paths that would eventually converge but are designed to ensure separation to their respective runways. This action may generate a conflict alert as the aircraft approach head-on because the automation predicts that a collision could occur if they continue their current trajectories, even though they will continue turning to their parallel inbound final approach paths.

Unreliable automation may lead to *trust failure*, in which the operator is reluctant to use the system. One practical effect of trust failure may be a decreased response to signals with a high false-positive rate (i.e., when the system generates a signal that does not require the operator to take action). *Systemwide trust failure* is caused when a failure of one component of a system disrupts trust in the other parts of the same system (Geels-Blair, Rice, and Schwark, 2013; Keller and Rice, 2010; Rice and Geels, 2010). This series of studies revealed that when operators were exposed to automation errors (false alarms or misses) in one signal, they began to quickly lose trust in the other 7 signals that were part of that system, despite the reliability levels remaining perfect for the remaining seven signals.

Automation, Workload, and Signals

Controllers routinely work with automated systems that use conflict detection and other algorithms to maintain aircraft separation, provide safety alerts, and help pilots avoid hazards. Although controllers rely on automation to improve safety and efficiency, they do not passively wait for the signaling algorithms to alert them to an ongoing or future event. They maintain vigilance while monitoring the trajectories and altitudes of aircraft under their control for potential hazards, often resolving them before a signal is activated. Controller workload may be decreased when the automation is working as intended but can increase abruptly if the automation is degraded or fails. Situation awareness and an operator's ability to diagnose and manage a problem are also affected if the automation fails. A person's cognitive skills may deteriorate as he or she becomes increasingly reliant on automation, making an accurate and timely response even more difficult during automation failures. The level of automation used in any system therefore represents a trade-off between improved routine performance, workload, situation awareness, and manual skills (Onnasch, 2014).

When engaged in a surveillance task, operators often use a combination of proactive and reactive interventions to adapt to a demanding task environment (Strickland *et al*., 2019). Controllers frequently identify a potential problem and proactively take steps to mitigate it before a signal is activated, but also rely upon prospective memory to accomplish this task. Boag *et al* (2019) found that controllers who perform a simulated conflict detection task share cognitive resources between ongoing safety-critical tasks and tasks that require prospective memory in proportion to their relative importance: They allocate most of their cognitive capacity to the task with the highest priority. In a study of prospective memory in air traffic controllers, aids that were set to flash when controllers were required to accept a target aircraft reduced prospective memory error and improved performance in simultaneous tasks that included aircraft acceptance and conflict detection. Memory aids that did not specifically alert the subjects when a target aircraft was present did not improve performance. (Loft, Smith, and Bhaskara, 2011) Signals should therefore be activated at the correct time so that they can aid controllers' prospective memory.

The environment in which controllers work may itself affect performance. Interpreting degraded speech, for example, negatively affects cognitive processing. Air traffic controllers are often required to respond to radio transmissions may be difficult to understand due to signal propagation, multiple simultaneous (“stepped-on”) transmissions, or background noise. They are also required to interpret speech under the adverse listening conditions of a noisy environment. In one study, young adults who listened to normal speech were better able to remember long strings of digits than those who listened to spectrally degraded speech. The same study also found that increased *extrinsic cognitive load* (adding a task that requires cognitive resources) impaired subjects’ ability to recognize degraded speech. The effort used to listen to and interpret degraded speech impaired working memory and required the reallocation of limited cognitive resources (Hunter, 2018).

Cognitive workload and background noise affect an operators’ ability to respond to signals. Increasing workload decreases and alters an individual’s field of view. (Williams, 1982; Rantanen, 1999) Although controllers use headsets for most communication tasks, there are often conversations occurring in the background, for example conversations between D- and R-side controllers or a controller using a loudspeaker for a landline conversation. Various signals may also be heard over a loudspeaker. This background noise may also affect prospective memory (remembering to perform a specific task at a future time). Background noise in the ATC environment may arise from multiple alarms or speech originating from the radio or from an adjacent controller. Even irrelevant sounds can disrupt attention, cognition, and prospective memory, and have been shown to impair tasks such as proofreading and language comprehension. The disruption caused by irrelevant sounds is enduring and does not decrease over repeated exposures. The disruptive effect of background noise may be primarily caused by the need for additional cognitive resources to determine which sounds can be disregarded (Banbury, 2001). One study of medical signals concluded that participants’ ability to identify and localize simulated alarms was best in quiet conditions during which there was no secondary task. Performance was worse during a secondary task (reading or mental arithmetic) while a recording of intensive care unit noise was played in the background (Edworthy, 2018). Background “noise” may, however, provide information that is valuable in a complex environment. Railroad operators routinely “listen in” to other conversations to learn of situations that may affect them in the future (Roth, 2006). Air traffic controllers also build situation awareness by overhearing conversations between pilots and other controllers in adjacent sectors (Kontogiannis, 2013).

Chapter 2: Signaling Philosophy

Potential Enhancements and Signaling Philosophy

Controllers work with many systems, including airport and airspace surveillance systems and equipment that monitors the status of their automation, and each type of equipment uses signals to alert the controller to a possible hazard. An integrated approach that considers every piece of equipment in the operational environment will help to minimize confusion about alarms. A review of the literature, analysis of ASRS reports, and controller interviews have identified specific problems and possible solutions that can enhance controllers' ability to maintain safe operations. This chapter also offers suggestions for minimizing alarm fatigue that are valid across domains.

The overarching goal of a signal philosophy is to improve controller performance and safety, improve controller trust in the system, and reduce controller workload. The philosophy that we propose in this handbook includes options for new signal sounds (Bennett, 2019), visual displays, and/or tactile feedback as well as strategies for managing existing signals. These findings may also be used to enhance the effectiveness of signals in the ATC environment by reducing repetitiveness, redundancy, unnecessary signals, and conflicting information. In addition to the discussion below, Appendix B contains a list of enhancements that includes whether they are currently used in air traffic control, other domains within aviation, and for non-aviation industries. The literature review in Chapter 1 and a study of near misses related to signals (Ruskin *et al*., 2021) suggest that there are opportunities for enhancement in the existing air traffic control signaling system. Goel, Datta, and Mannen (2017) have suggested that the utility of a signal can be evaluated according to specific characteristics:

- **Uniqueness**: Each signal should indicate deviation from a unique parameter. Duplicate and overlapping signals should be avoided.
- **Prioritization**: Each signal should clearly indicate its priority level.
- **Timeliness**: Signals must appear at the correct time. A signal that is activated too early or too late may prevent the controller from making the correct response and may decrease trust in the system.

- **Understandability**: A signal should have an easy-to-understand description that clearly indicates the hazard.
- **Relevance**: Each signal should be relevant and should also have operational value to the controller.
- **Required response**: A signal should require a definitive response from the controller.

Meeting these requirements means that the signal must convey the nature of the problem, the locations and altitudes of the involved aircraft or vehicles, and the urgency of the problem. We suggest that signals can be divided into four categories that require increasing levels of intervention by the controller:

- **Priority 1**: Immediate danger requiring urgent controller intervention. (*e.g,* Imminent NMAC, flight below MVA, AMASS)
- **Priority 2**: Risk of harm. Controller intervention will be required soon (*e.g.*, Predicted conflict, airspace alert)
- **Priority 3**: Informational. Intervention may be required (*e.g.*, Mode C intruder)
- **Priority 4**: Diagnostic or equipment failure (*e.g.*, Radar outage, localizer malfunction)

A variety of cues can be used to indicate alarm priority, including pitch, timbre, and verbal indicators. The ideal auditory signal is easy to localize, does not interfere with communication, is distinguishable from other alarms, is not easily missed, is resistant to masking by other sounds, and is easy to learn. Hansen *et al*. (2021) found that for high-priority, emergency alarms, augmentation with digitized human speech decreased response time. For lower-priority, less reliable signals, a slight delay before activation improved operators' performance.

Both the structured interviews and ASRS reports have indicated that misses can arise from silencing or suspending alarms. This suggests that facility policy and operational guidance could be developed as to when and how a signal for a discrete hazard could be permanently silenced or temporarily suppressed in the tower, TRACON, and en route environments. This policy may also help to inform strategies that can improve trust in the automation, such as designing signals to indicate the level of confidence that the automation has in the likelihood of the hazard (e.g., that the automation has in predicting an impending loss of separation (Borst, 2017)). If the controller is allowed to suppress an auditory signal, the data block should continue to show that the underlying situation is still present. Controllers should be provided with the ability to suppress a signal by informing the automation that a resolution has been implemented. For example, the controller might indicate that two aircraft have agreed to maintain visual separation or that formation flights will manage their own separation despite having discrete transponder codes. Subsequently, the auditory portion of the signal should automatically re-enable if the situation remains static or progresses, except in limited cases (*e.g.*, formation flight). Whenever a signal can be suppressed or its parameters modified, controllers should be able to obtain information about the status of that signal. Status information should be readily available when responsibility is shifted from one controller to another.

Environmental Limitations

The environment in which the controller is working affects the types of signals that can be used. For example, air traffic control towers have variable lighting, depending upon the time of day and the orientation of the tower. Visual signals may therefore not be as effective in attracting the controller's attention, especially during the day. Critical systems may be located in different areas of the tower cab, requiring the controller to move from one piece of equipment to another, especially when multiple signals are activated at once. Local and ground controllers in an air traffic control towers are also mobile, limiting the effectiveness of technologies such as tactile stimuli or highly directional audio. Some touch-screen displays may cause colors to be washed out or otherwise altered when observed from an oblique angle. To mitigate these effects, the priority of signals should be encoded with shapes as well as colors. For example, signals could be encoded as: Priority 1 [Red square], Priority 2 [Yellow triangle], Priority 3 [Orange nabla], Advisory [Cyan diamond] and Suppressed [Circle coded with color of alarm].

Environmental limitations might make some signaling modalities more effective in specific domains (Ruskin et al., 2020). For example, indicator lights and messages on screens may be less effective in a control tower because bright light makes them more difficult to see. This environment may therefore benefit from additional use of auditory signals while designing enclosures that enhance the visibility of screens and lights. Tactile displays (*i.e.*, those using the sense of touch) may be used instead to draw a controller's attention to an urgent condition, but the design of these devices must accommodate controllers who move between stations.

Improving the localizability of auditory signals may help controllers diagnose a problem more quickly. One relatively simple and cost-effective way to test these potential enhancements before further development would be to use a cognitive walkthrough study as described by Hah *et al*. (2017). For an impending situation that involves a high risk of harm, signals can offer suggested actions (*e.g*., ASDE-X “Go Around!” alarm). In addition, the simultaneous use of multiple modalities might be valuable when response time is critical and there are urgent and high-workload challenges (*e.g.*, aircraft in distress, multiple landline calls to coordinate) that may distract the controller. Using voice alerts for extremely high-priority alarms indicating potential loss of life has been shown to reduce response time in domains outside of aviation. (Hansen *et al*., 2021)

The automated systems used in each ATC environment determine how signals are generated and presented. For example, current STARS and ERAM systems allow controllers to suppress the conflict alert. When the conflict alert is silenced, the display continues to indicate that the algorithm has detected a potential loss of separation, but the data block stops flashing, and auditory signals are silenced. The controller is permitted to suppress this signal until the conflicting aircraft have violated the standard separation requirement, after which the signal can no longer be suppressed, and the controller must intervene to separate the two aircraft. STARS and ERAM CA use different algorithms to detect possible conflicts, both of which use surveillance data and dead reckoning to predict aircraft trajectories. The ERAM Conflict Probe uses advanced trajectory modeling, surveillance data, and route information to provide an alert up to 20 minutes before a potential conflict. The ERAM Conflict Probe does not, however, account for situations in which greater separation may be needed (*e.g.*, non-standard formations or very heavy aircraft such as the Airbus A380) or where reduced separation is permitted (*e.g.,* formation flight).

Signal Strategies

Auditory Signals

The acoustic structure of signals affects their ability to effectively draw the operator’s attention to a hazard. The *cohort theory* of sound recognition suggests that an initial sound (or melody) activates a cohort of possible matches in a person’s mind. This list of possibilities is then narrowed as the sound progresses. A person identifies the specific word (or melody) after all other candidates have been eliminated. (Schulkind *et al*., 2003) The most basic delineation of auditory signals is between speech-based and non-speech-based sounds. Speech-based signals have the advantages of being easy to understand without the need to use abstract sounds (Leung, 1997), while signals that do not rely on speech are language-independent and recognizable in a cluttered acoustic environment. (Oleksy, 2018) Making signals more acoustically rich and explicitly encoding their urgency can improve their performance. Features of a signal's melodic structure (*e.g.*, repeated notes, changes in amplitude, and easily recognizable intervals) can increase the likelihood that an operator will identify it correctly. (Gillard and Schütz, 2016) Rayo *et al*. (2019) also found that timbre can be used to encode alarm similarity and urgency, improving identifiability of different alarms. Heterogenous auditory signals are also easier to identify than using a single sound for multiple conditions (Edworthy, 2011). Potential methods of creating unique sounds include varying timbre, using chords (in a minor key), changing pulse length, or varying amplitude. Using acoustically rich signals sounds may therefore improve controllers' performance, particularly in a noisy environment or when multiple signals are being activated at once.

Improving the localizability of alarms can help controllers to determine where a given event is occurring. Binaural alarm systems that are designed to incorporate spatial cues may also help operators to identify a signal in an environment with high levels of background noise. (Uchiyama *et al*., 2007) Highly directional loudspeakers can help to reduce the overall noisiness of the environment by producing sounds that can be heard only in a narrow range (Shao *et al*., 2021). Humans are best at localizing sounds below approximately 2 kHz, and above 5 kHz, suggesting that signals should use frequencies in this range (Grothe, Pecka, and McAlpine, 2010). Catchpole, McKeown, and Withington (2007) found that adding broadband noise components to an auditory warning pulse can enhance information about the location of a signal, although there was a trade-off between the listener's ability to localize the signal and its perceived urgency.

New classes of auditory signals, including earcons and spearcons, may help controllers differentiate between different conditions and the urgency of a hazard. An *earcon* (or auditory icon) is a non-verbal auditory message that is used as part of a human-computer interface to provide information and feedback. The paper-crumpling sound many computers make when dragging a file to the trash is an example of an earcon (Blattner, 1989). Earcons are easy for operators to learn, especially when their sound correlates to a specific target event. (Keller and Stevens, 2004) In one study, non-physician participants quickly identified abnormal vital signs indicated by earcons while monitoring a series of simulated patients (Hickling, 2017). Graham (1999) found that earcons produced significantly faster reaction times than conventional warnings during simulated driving. However, earcons produced an increased number of inappropriate responses, in which drivers reacted by braking in response to a situation in which a collision was not imminent. The findings are explained relative to the perceived urgency and inherent meaning of each sound. A *spearcon* consists of artificially accelerated human speech and combines features of earcons and the spoken word (Walker, 2013). Spearcons can improve a user's ability to navigate menus and may be superior to other auditory cues. Although signals based on spearcons have not yet been evaluated in aviation, one study in medicine concluded that spearcons improved participants' ability to monitor multiple patients for abnormal conditions (Li, 2019).

Visual Signals

Modifications to visual signals can help controllers to identify and prioritize situations that require their attention. An easily accessible alarm summary window can provide a list of current situations requiring a controller's attention, especially when alarms have been suppressed. A visual indicator as to the potential risk and the speed at which a situation is developing may help controllers to prioritize multiple situations in parallel. For example, a bar underneath the data block of an aircraft about to enter an area with a higher MVA might indicate the amount of time remaining before a controller must either issue a climb instruction or vector it away from the obstruction. This "time to go" indicator can help the controller to manage the situation by providing the controller with an indication of how long he or she has before the problem becomes critical (*e.g.*, loss of separation). Such an indicator may consist of a progress bar or a circle, and its visual characteristics could be used to indicate the urgency of the problem. For example, stimuli that accelerate toward the end of their movement are perceived to be changing more rapidly than stimuli that are moving at a constant rate. (Matthews, 2011)

Tactile Signals

Tactile alerts have been shown to improve performance in an automated cockpit environment, producing a higher detection rate of, and faster responses to, potential failures. Operators' response to tactile alerts may be unaffected by concurrent visual tasks. (Sklar, 1999) Visual-tactile alerts seem to work best in a multitasking, high-workload environment. (Burke, 2006) Lane-departure warning systems in cars often use visual-tactile signals such as graphic warning displays on the dashboard paired with a vibration in the steering wheel to alert the driver when vehicle sensors detect that the car is deviating from the lane and starting to cross lane markings. These systems are only triggered when the turn signal has not been activated to indicate an intent to change lanes. Tactile signals using wireless, wrist-worn devices may be feasible even in users who require mobility (*e.g.*, tower controllers) (Lee and Starner, 2010).

Chapter 3: Human Performance Principles

Signal Implementation Process

The specific features of a signal and the process by which it is designed and implemented can enhance its effectiveness. A controller's workstation should present signals so that the controller can easily understand their priority (e.g., urgency and severity of the hazard) and whether a signal is new or has been acknowledged or cleared. The FAA's Human Factors Design Standard documents a process for incorporating human factors into equipment design, while the ANSI/ISA-18.2 standard was developed to guide performance benchmarks for industrial alarm systems. (Wang, 2016) The ISA standard recommends 10 stages for an alarm management lifecycle:

- Development of a signal philosophy
- Identification of signal states
- Rationalization
- Detailed design
- Implementation
- Operation
- Maintenance
- Monitoring and assessment
- Management of change
- Audit

This chapter will discuss each of the ways in which signals can be presented in the ATC environment and their implications for human performance. The next chapter of this handbook will provide guidance on how human performance experts and subject matter experts can work together on the Rationalization, Detailed Design, and Implementation stages. The framework that we describe will provide a common language for all personnel involved in signal design and use to develop the specifications that equipment designers can then use to create prototype signals.

Signal Presentation

Auditory

Audio signals should be designed to quickly attract the controller's attention to the hazard while minimizing a startle response. They should reliably capture the controller's attention without being unpleasant. Auditory signals should be unambiguous and easily distinguishable from one another using unique combinations of tone pattern and frequency for nonverbal signals. In addition to being easily distinguishable, new signals can be designed to carry additional information such as urgency (e.g., by varying their tempo) or even a desired action, in the form of a spoken alert (such as the AMASS "Go Around!"). The frequencies of auditory signals should be widely spaced within a range of 500 to 3,000 hertz (Hz), as sounds in this range are easiest to localize (Risoud *et al*., 2018). Loudness affects the saliency of auditory signals. High levels of ambient noise in an environment impair working memory (Banbury *et al*., 2001). Routine office noises such as ringing telephones also impair concentration (Banbury and Berry, 2005). Humans can easily localize sound in specific frequency ranges (Risoud *et al*., 2018). In general, humans localize low-frequency stimuli (centered on 250 Hz) with the highest accuracy and are almost as good at localizing high-frequency tones (centered on 4000 Hz). People have the most difficulty localizing mid-frequency stimuli (centered on 2000 Hz) (Yost, 2016).

In general, the volume of auditory signals should exceed the prevailing ambient noise level by at least 10 dB(A) or any maximum sound level with a duration of 30 seconds by at least 5 dB(A), whichever is louder, without exceeding 115 dB(A) for emergency signals or 90 dB(A) for other signals (Allendoerfer, 2007). The volume control for auditory signals should be restricted to prevent controllers from reducing the sound to an inaudible level (unless the signal is being suppressed) or increasing it to an unacceptably high level. One way to determine the permissible volume levels would be to monitor the ambient noise levels in representative facilities during times associated with peak traffic levels and incorporate this information into equipment designs. Another, possibly more effective, solution would be for new equipment designs to another measure the ambient noise level and dynamically adjust the sound level of auditory signals.

Modern loudspeakers can easily produce high-quality sounds that are loud enough to be noticeable in a very small space (Bahne, 2012). The number and placement of loudspeakers should be such that auditory signals are free of distortion and are clearly audible at the controller's workstation. Although auditory signals may only need to be heard by a single controller in a TRACON or ARTCC setting, some signals in an air traffic control tower (*e.g.*, AMASS auditory alerts) may need to be heard by all personnel. If the auditory signal will be presented through a loudspeaker, it should be oriented in a direction that is away from surfaces that could scatter or diffuse the sound. Loudspeakers should not be located behind structures that could cause distortion, echoes, or sound shadows. When the sound is used to direct the controller's attention to a specific location, the loudspeaker should be oriented so that it can easily be identified by the controller and should correspond to the location of the intended alarm display. Loudspeakers for adjacent alarm display devices should have adequate separation to allow controllers to discern their individual locations.

Although some signals should be suppressible under specific circumstances, this feature should be temporary, essentially working as a "snooze" function and not removed entirely. If a controller is able to suppress a signal after it activates, it should reactivate if additional criteria are met, such as elapsed time (*e.g.*, if the suppressed aircraft are still in CA status after a preset length of time has elapsed) or urgency (*e.g.*, if the suppressed aircraft are projected to lose separation in 30 seconds instead of 75 seconds). Signals that already meet the criteria that would inhibit suppression at the time of their first activation would not be suppressible. For example, if two aircraft are projected to lose separation in 45 seconds, the signal would not be suppressible.

Visual

The urgency of a signal can be indicated by its color, position, shape, or use of special symbols. For example, data blocks associated conflict alerts turn red in the ERAM system. A controller should be able to quickly find critical information in the data block, and it should be legible and easy to interpret. One way to indicate urgency is to alter the color of the data block, for example to distinguish data blocks associated with a CA or MSAW from other aircraft. Text that is presented in red may convey more urgency than yellow or blue text, so this may also be used to indicate urgency. (Chan and Ng, 2009) Safety Orange is typically used as a warning color for road signs or other safety applications because it is highly saturated and easy to track. (Braun, Mine, and Silver, 1995; Fisher, 2021) Accurate color interpretation relies on many factors, including ambient lighting, display accuracy, viewing angle, and the controller's ability to discriminate color. This technique should therefore be considered in combination with other information, such as text. Visual signals should not be used by themselves to alert the controller of an urgent hazard as auditory tasks (e.g., listening to conversations on a busy frequency or conducting a relief briefing) may cause inattentional blindness to unexpected visual signals. (Pizzighello and Bressan, 2008)

Alert data blocks can indicate urgency by flashing to attract the controller's attention, with the urgency of the hazard indicated by the flash rate (Chan and Ng, 2009). Chan and Ng (2009) found that in addition to the color of an illuminated indicator, its flash rates, flashing pattern, and combination with auditory alerts contributed to urgency. In this study, a red flashing light was perceived as the most effective hazard warning. Increasing the flash rate increased the perceived hazard. Faster flash rates were more effective, and the ideal frequency in this study was a flash rate between 180 and 240 flashes per minute, with 240 the most effective. An irregular pattern (e.g., a double or triple flash pattern) also increases the noticeability of the signal. Prior FAA studies have suggested that flashing text should quickly attract the attention of the controller while maintaining good legibility. These publications recommend 1/3 to 1 flash per second with a duty cycle of 70% (Ahlstrom & Longo, 2003, section 8.6.11.9). If only a symbol is flashing, a faster flash rate can be used, such as 2 to 5 flashes per second with a duty cycle of 50% (Ahlstrom & Longo, section, 8.6.11.3). The system should allow controllers to stop data blocks from flashing with a keyboard or trackball entry, while the data block continues to indicate that it is associated with a hazard.

Data blocks indicating an alarm should provide all relevant aircraft data, so that the controller will have as much as information as possible to resolve the hazard. Data blocks associated with a hazard should be placed higher on the screen than data blocks of non-hazard aircraft or other displayed information so that they are continuously visible and highly salient. These data blocks should be displayed at the size that provides optimum legibility, which Ahlstrom & Longo (2003) determined to be 20 to 22 minutes of arc, and they should be displayed at a brightness that provides optimum contrast, especially in a brightly lit facility. Lastly, graphical objects may help to provide controllers with a quick and easy to understand indication of the level of the hazard and the amount of time remaining to address it. (Burns & Jessa, 2007)

Tactile

Tactile signals can potentially be used to alert controllers to a particularly urgent hazard, such as an imminent loss of separation. Multiple signaling modalities including tactile alerting might also be used to indicate a particularly urgent condition that requires a rapid response. For example, both auditory and tactile stimuli might alert a controller to an aircraft in distress (*e.g.*, squawking 7700) or a runway incursion while another aircraft is attempting a takeoff or landing. Unanticipated tactile alerts can be startling, however, and maintaining vigilance for tactile alerts may also be stressful (Horberry *et al*, 2021, DeLucia, 2020), although Pratt *et al.* (2012) describe a method of indicating urgency without unnecessarily annoying an operator by varying the pulse rate of vibrotactile stimuli. In general, users of tactile alerting devices can discern temporal alert patterns but have more difficulty perceiving changes in intensity (Lee and Starner, 2010). This signaling modality has not been used in the ATC environment and would therefore require additional study prior to implementation.

Graded Signals

There is some evidence that the effects of nuisance and false signals can be mitigated by using graded and likelihood alerts (Gupta, Bisantz, and Singh, 2001). The presentation of signals can vary with the urgency or the severity of its associated hazard. For example, a minor problem that is projected to occur relatively far into the future might receive the lowest level of signal while a potentially life-threatening hazard that is projected to occur very soon would receive the highest alert level. Although this technology has yet to be incorporated into ATC systems, graded alarms improve lateral vehicle control and reduce skids when used in automobile collision alert systems. (Gupta, Bisantz, and Singh, 2002) In addition to possibly enhancing controllers' trust in their signals, grading signals will help to mitigate the effects of nuisance signals. Because some common situations (e.g., an aircraft on a published instrument approach in which one of the segments is below the trigger for the MSAW) will receive the least salient presentation, some nuisance signals may be avoided. Because the signal presentation with the highest saliency will be reserved only for the most severe hazards, controllers may be less likely to disable them by turning down the brightness or volume because they will be exposed to them only infrequently.

Alarm Fatigue

An excessive number of false alarms may lead the operator to disregard the importance of a signal. Although Wickens *et al*. (2009) suggested that the "cry wolf" effect may not be as harmful as previously thought in the ATC environment, their study was limited to conflict alerts.

One of the ASRS reports in our study of signals in air traffic control suggests that the "cry wolf" effect may occur in the Tower environment with some misleading signals generated by AMASS (Ruskin *et al*., 2020). The ASRS narrative report, which describes how false ASDE-X alarms may reduce the response rate to conflict alerts or MSAWs, also suggests that an excessive number of false or misleading signals may cause systemwide trust failure (Keller and Rice, 2010). Conversely, reports and structured interviews suggest that controllers usually respond to a developing situation before an alert is activated. This finding is consistent with a study by Allendoerfer *et al*. (2008). This effect may be mitigated by indicating the automation's level of confidence that the signal represents a situation that will require intervention on the part of the controller. For example, an ARTCC's Conflict Probe alert for two targets that might converge in 30 minutes might indicate a lower likelihood than would a Conflict Alert for two converging targets that are less than six miles apart.

Alarm Flood

The International Society of Automation standard ISA 18.2 defines *alarm flood* as "A condition during which the alarm rate is greater than the operator can effectively manage (e.g., more than 10 alarms per 10 minutes)." During an alarm flood, the number of alarm events occurring in a short time overwhelms the operator, preventing him or her from promptly managing all of them (Xu, Wang, and Yu, 2019). Alarm flood can be avoided by inhibiting multiple alarms that may arise from the same deviation. Implementing a summary visual display of all the signals associated with a given hazard, combined with a single audible alarm may also help to reduce alarm flood.(Laberge, 2014). Controller training should also include a strategy for responding to multiple, simultaneously activated signals.

Trust

Operators trust an automated system when it performs as expected. If the operator understands what the system is doing, he or she is better able to maintain vigilance for rare and potentially catastrophic automation failures. In this way, improving the level of transparency helps to maintain operators' trust in a system. Some ways to improve transparency include designing a signal to provide an indication of why it is being presented, the likelihood of the condition, and the urgency of the condition. Likelihood alarms in particular have been shown to improve an operator's ability to allocate attention between two different tasks, improving their performance. (Wiczorek and Manzey, 2014)

Chapter 4: Signaling Framework

This chapter describes a novel, objective, and comprehensive framework for alarm design or evaluation. This framework is designed to be used by subject matter experts and human factors professionals to interview air traffic controllers (or experts in other domain) and provides a common language by which alarms can be described and evaluated. The framework also provides a permanent record of the decisions made during alarm design or evaluation process. In the past, specialized alarm taxonomies have been developed for research purposes (Bliss *et al*., 2014; O'Hara & Fleger, 2020) and many authors have suggested specific changes to alarms in the medical and aviation domains (Edworthy, Parker and Martin, 2022; Fitzgerald *et al*., 2019; Vincent and Blandford, 2014). Ruskin and Hueske-Krause (2015) have previously described medical alarms in the context of several taxonomies, including Bliss and Xiao and Seagull (1999). However, the framework presented in this chapter, designed by the authors for the Federal Aviation Administration and air traffic controllers, is the first to link the user needs to alarm design.

The signaling framework consists of 15 properties in five categories: *How*, *What*, *Where*, *When*, and *Why*. Using the framework involves first choosing the signal of interest (e.g., the conflict alert in a TRACON environment). A human factors professional then uses the framework and its associated structured interview that allows air traffic controllers (or subject matter experts in other domains), human factors professionals, and system designers to objectively score a new or existing signal. The framework includes quantitative and qualitative components, each of which is then incorporated into a written record that provides comprehensive, permanent documentation of the rationale for each design feature. This record can later be referenced to understand the original intentions of the subject matter expert and the designer when a signal must be modified to account for changes to the equipment or environment. It is also useful when creating additional signals in the same category. This framework also provides controllers, human factors experts, and equipment manufacturers with a common language to describe, classify, and objectively evaluate and design signals that will be used throughout the ATO.

CATEGORY #1: HOW (How should the alarm notify the air traffic controller?)
MODALITY, PRIORITY, SALIENCY, and DISRUPTIVENESS

Modality

The *modality* of the signal is the means used to present that signal to a controller. For example, a signal can be presented using one or more visual, auditory, or tactile stimuli. Although visual signals are often effective, auditory signals may be superior when it is necessary to the operator's attention in specific circumstances (Lazarus and Höge; 1986; McNeer *et al*., 2007; Wright et al., 2020). There is some evidence that auditory signals may be more effective in communicating urgency (Morris and Montano, 1996), and may even attract attention when set to a volume below the ambient noise level (Schlesinger *et al*., 2018). In some cases, particularly for high-priority signals, both visual and auditory modalities may offer redundancy. Adding additional sensory modalities such as visual or tactile signals to an auditory signal can enhance its perceived urgency (van Erp, Toet, and Janssen, 2020).

Priority

Some signals may have priority over others in settings where multiple signals may be activated. The priority of each signal therefore depends on the urgency and severity of the hazard. Signals that are paired with hazards with the highest urgency or severity (usually alarms) should be assigned a higher priority than those that can be managed later (usually alerts). For example, a CA that indicates an imminent risk of collision might be assigned a higher priority than one indicating a potential loss of separation.

Saliency

Saliency refers to a signal's prominence, or "the quality of being particularly noticeable or important" (McKean, 2005), and indicates how easily a controller can detect the signal. Displays that share common features with their backgrounds have low saliency and are more difficult to detect. In contrast, signals with high saliency have unique features that allow them to stand out from the background (Treisman and Gelade, 1980) and are easily noticeable, even when surrounded by distractors or clutter (Wolfe and Horowitz, 2017; Wolfe and Kluender, 2018). Signals that require an immediate response should be designed to incorporate high saliency. In contrast, a signal indicating a lower-priority condition may be designed to incorporate a lower level of saliency but should still be easy for the controller to recognize under low workload conditions.

Factors that affect saliency include color, contrast, and size (for visual) and amplitude (for auditory displays). Too little contrast makes it difficult or impossible to detect objects. Decreasing amounts of contrast requires that an individual expend more effort to detect an object, and detection performance decreases (Rice *et al*. 2012). One way to easily increase the visual contrast between two objects is to provide a feature that distinguishes the target from the background (Amesbury and Schallhorn, 2003). The effect of brightness of a visual signal on its saliency is affected by its environment. For example, an illuminated indicator may be distracting in a dimly lit radar room, but an indicator with the same brightness may not be visible in a control tower during the day. Moreover, pairing auditory and visual stimuli can affect the way that both are perceived (Watanabe and Shimojo, 2001).

Color is an important stimulus for saliency and attention in people who do not have color vision deficiencies (Law, Pratt, and Abrams, 1995; Aziz and Mertsching, 2007) and can therefore be used to indicate a signal's urgency. In one study, a red flashing light was perceived as the most effective hazard warning; participants felt that yellow and blue warning lights indicated a less hazardous situation (Chan and Ng, 2009; Ng and Chan, 2018). Color can be used to provide contrast against a background, but only if the correct color combination is used. For example, Safety Orange is not common in nature and contrasts well with most backgrounds (especially azure, which is the color of the sky), which is one reason why this color is chosen for traffic warning signs. The size of a visual signal also influences its saliency and should be selected to make it easily noticeable in the intended environment.

The shape of a visual signal can affect its saliency and has been studied in the design of warning labels (Riley, Cochran and Ballard, 1982). In a study of warning labels, participants associated a triangle with the highest perceived hazard level. An inverted triangle, octagon, and rhombus indicated a lower hazard level to the study participants (Chen, Liu, and Huang, 2015). Humans are more likely to notice and process objects well-defined outlines and sharp edges (Vinberg and Grill-Spector, 2008). Common shapes of visual signals include circles, octagons, triangles, and squares. Using different shapes to indicate specific hazards may also help controllers who have a color vision deficiency to identify a specific signal.

Features that affect saliency include:

Contrast (visual, tactile). Humans require sufficient visual contrast between an object and its background to detect that object (Amesbury and Schallhorn, 2003). Decreasing amounts of contrast cause an individual to expend more effort and impairs their ability to detect the object. (Rice, et al. 2012).

Color (visual). Color is one of the most important features that stimulates the visual system in humans (Aziz and Mertsching, 2007; Law, Pratt, and Abrams, 1995). Color can be used to indicate the urgency of an alarm. A red flashing light more effectively indicates a hazard warning than yellow and blue warning lights (Chan and Ng, 2009). Certain color combinations create a more effective contrast. For example, yellow contrasts well with most backgrounds except for green and orange, which is one reason why this color is chosen by schools (for small children), cyclists, construction workers, etc. Changing one feature (color) increases detection accuracy and decreases response times. This is an example of the Pop-out Effect, which results in *attentional capture* (Hsieh, Colas, and Kanwisher, 2011).

Size (visual). The size of a visual alarm influences its saliency and enlarging a data block may be one way to attract a controller's attention to a potential hazard. Increasing the size of a signal may not be possible in some circumstances, however. For example, an ATC radar display has a limited amount of space that must accommodate airspace, traffic, and other notifications.

Shape (visual). The shape of an alarm may also influence its saliency and has been studied in the design of warning labels (Riley, Cochran, and Ballard, 1982). The human visual system is more likely to be stimulated by and process objects that have well-defined outlines and sharp edges (Vinberg and Grill-Spector, 2008). Many visual alerts/alarms are round, and additional common shapes include octagons (stop signs), triangles (yield signs) and squares (road and information signs). These shapes are not commonly found in nature and therefore provide contrast with surrounding objects, possibly increasing their saliency in the visual cortex (Beck and Kastner, 2005). In a study of warning labels, participants associated a triangle with the highest perceived hazard level. An inverted triangle, octagon, and rhombus indicated a lower hazard level to the study participants (Chen, Liu, and Huang, 2015). Using different shapes to indicate specific hazards may also help operators who have a color vision deficiency to identify an alarm.

Luminance (visual), *Amplitude/volume* (auditory, tactile) *and Frequency* (auditory, tactile). Illuminating an alarm can increase its saliency (O'Hara 2020), particularly during low-light or nighttime viewing. An alarm should be designed to have sufficient illumination in the presence of factors (*e.g*., dust) that may negatively affect its luminance. Amplitude is an important consideration for auditory signals. As previously described, however, high levels of ambient noise in an environment impair working memory (Banbury *et al*., 2001), as do routine office noises such as ringing telephones (Banbury and Berry, 2005). Humans can easily localize sound in specific frequency ranges (Risoud *et al*., 2018). In general, humans localize low-frequency stimuli (centered on 250 Hz) with the highest accuracy and are almost as good at localizing high-frequency tones (centered on 4000 Hz). People have the most difficulty localizing mid-frequency stimuli (centered on 2000 Hz) (Yost, 2016).

Texture (tactile). The texture of a tactile signal may provide some additional salience. Multiple efforts are underway to develop vibrotactile displays that can indicate different textures (Asano, Okamoto, and Yamada, 2014).

Speed, Pattern, and length (visual, auditory, tactile). The speed, pattern, and length of an alarm influences its perceived level of urgency. Chan and Ng (2009) found that in addition to the color of an illuminated indicator, its flash rates, flashing pattern, and combination with auditory alerts contributed to urgency. In this study, a red flashing light was perceived as the most effective hazard warning. Increasing the flash rate increased the perceived hazard. Faster flash rates were more effective—the ideal frequency in this study was a flash rate between 180 and 240 flashes per minute, with 240 the most effective. An irregular pattern (*e.g.*, a double or triple flash pattern) also increases the effectiveness of the alarm. For example, one study found that "stutter flashing," or irregularly flashing LEDs, were more effective at causing drivers to yield to pedestrians in crosswalks (Van Houten, Ellis, and Marmolejo, 2008).

Disruptiveness

An effective signal must attract the controller's attention but should not so intrusive as to interfere with the controller's ability to perform tasks. Alarms indicate an urgent hazard that must be addressed immediately. They therefore have a higher priority and should be more disruptive than alerts. Disruptiveness can be a liability during conditions of alarm flood, when multiple alarms occur simultaneously. This occurs commonly in medical environments such as the operating room and intensive care unit (Simpson and Lyndon, 2019). Alarm flood has also been well described in the setting of industrial process control and several potential solutions have been developed (Laberge, 2014; Guo *et al*., 2017). The disruptive nature of alarms can grow exponentially when multiple alarms are vying for the controller's attention at the same time.

CATEGORY #2: WHAT (In what way should the alarm notify the air traffic controller?) DISTINGUISHABILITY, EXCLUSIVITY, FAMILIARITY/RECOGNIZABILITY, CONSISTENCY and INFORMATIVENESS

Distinguishability

Signals should be easily distinguishable from one another in environments where multiple alarms may be present. Poor performance of medical alarms in the intensive care unit and operating room has been attributed to a lack of distinguishability (Momtahan, Hetu, and Tansley, 1993). Signal designers can manipulate color, shape, size, and illumination of visual signals to enhance distinguishability, and can also manipulate the loudness, pitch, and timbre of auditory signals. Auditory signals may also include verbal signals or instructions.

Exclusivity

Exclusivity refers to whether the signal is limited to a single purpose or can be used for multiple purposes. Each signal should have exclusive presentation that does not change and is not paired with any other event. For example, the current MSAW and CA signals use pulsed tones of different frequency and duty cycles, which allows the controller to rapidly understand the hazard being indicated.

Familiarity/Recognizability

Controllers are more likely to recognize a signal with which they are familiar while new signals may take longer to recognize or may be confused with an existing signal. Existing signals should therefore be changed only when necessary for operational or safety reasons. Training can overcome some of these issues, as a person who is familiar with a given signal is more likely to respond accordingly.

Consistency

Some systems vary in their presentation of signals between different facilities or within the same facility. Signals should be consistent in their presentation and meaning so that a controller who is familiar with one type of automation can recognize a similar hazard regardless of the equipment being used.

Informativeness

Signals should inform the controller as to the nature of the hazard and may also provide instructions that provide the controller with information needed to take the correct action. Signals should provide relevant information about the nature of the hazard, the response required from the user, the amount of time remaining to resolve the issue, and some indication that the issue has been resolved. Particularly in the setting of an immediate, life-threatening hazard, the signal should provide only the information needed for the operator to manage the event while not overwhelming the controller with irrelevant data or other alarms (Laberge et al., 2014). Effective signals are designed to recognize that the user usually does not have time to process an avalanche of raw data. Signals may be designed to provide more information, depending on how rapidly the user must respond to them. For example, the AMASS alarm in air traffic control towers includes a verbal warning to alert the controllers to a potential runway incursion.

CATEGORY #3: WHERE (Where should the notification of the air traffic controller occur)
LOCATION and RECIPIENT

Location

High-priority visual signals should be placed directly in front of the controller so that they can be easily observed and facilitate a rapid response from the controller (SAE International, 2017). The location of an auditory signal is also important, and some hazards may require that an auditory signal be presented in multiple locations, particularly if the controller must move around a facility, as in an air traffic control tower. The controller's ability to localize a signal may be facilitated by incorporating lower frequencies (i.e., less than approximately 800 Hz) because inter-aural differences in phase and amplitude are used to localize sound (Moore, 1997). Using a wideband sound (i.e., more than one octave) may also make sounds easier for a controller to localize. (Yost and Zhong, 2014) Tactile signals may also be used to help the controller direct his or her attention to the correct location. For example, vibrotactile systems have been used to prevent spatial disorientation in helicopter pilots (Raj, Kass, and Perry, 2000), and helicopter pilots have reported improved situation awareness when using a tactile alerting system to facilitate hovering over a target (Kelley et al., 2013). Vibrotactile stimulators have also been proposed to help infantry soldiers to communicate and direct their activities during military operations (Elliott, Schmeisser, & Redden, 2011).

Recipient

The intended recipient(s) of a signal determines where the signal should be placed. If the recipient is in a single location, the signal can be placed in that location. If, however, the recipient moves to different locations or several people must receive the signal, these factors should be incorporated into its design. For example, TRACON controller working a single sector may be the only person who receives a CA. In contrast, several controllers in an air traffic control tower may need to be aware of an AMASS alarm. If the AMASS alarm is activated in that environment, other controllers (including a supervisor) may be able to help during a safety-critical event if they can hear the corresponding alarm.

CATEGORY #4: WHEN (When should the alarm notify and stop notifying the air traffic controller)
TEMPORALITY and SUPPRESSIBILITY

Temporality

A signal's temporality determines when it will be activated, how long it will be activated, and when it stops. In some situations, it may be desirable for the signal to activate immediately. For example, two aircraft that are rapidly approaching each other head-on requires that the controller take immediate action to prevent a collision. The CA might be delayed for two aircraft on approach procedures to parallel runways as long as they remain on a charted course that ensures separation.

Suppressibility

The ability of a controller to mute or disable a signal determines its suppressibility. Alarm fatigue has often been cited as a reason for suppressing alarms (Casey, Avalos and Dowling, 2018; Ruskin and Hueske-Kraus, 2015). Although some ATC systems are designed to prevent alarm suppression, controllers have been reported to cover signals that are designed to prevent deactivation with a piece of tape (Ruskin et al., 2021). Current ATC systems offer several methods of suppressing signals, with specific regulations that describe how and when a signal can be suppressed. For example, a controller can suppress the display of a CA/MCI alert from a control position using the Conflict Suppress (CO) function for specific aircraft that are generating an alert or the Group Suppression (SG) function to inhibit alerts for military aircraft engaged in operations in which standard separation criteria do not apply. In both cases, the act of suppressing the signal constitutes acknowledgment that the controller will take appropriate action.

CATEGORY #5: WHY (What should the alarm indicate about the hazard?)
PERCEIVED ACCURACY AND PERCEIVED RELIABILITY

Perceived Accuracy

Signal Detection Theory (SDT) is used as a foundation for understanding signal sensitivity and specificity (Green and Swets, 1966). Although it may seem intuitive that signals should always avoid misses at all costs, false alarms can often have a more detrimental effect on long-term trust. (Dixon, Wickens and McCarley, 2008; Keller and Rice, 2010; Rice and Geels, 2010). An ATC signal indicates that a specific threshold has been exceeded, and in most cases the controller should be notified of the corresponding hazard. A controller who does not trust a signal that generates excessive false alarms (Breznitz, 1984) may ignore or deactivate it. In some cases second-level engineering modifications can be implemented to reduce the incidence of nuisance signals. For example, an “inhibit area” can be created to prevent an MSAW from activating when aircraft are established on an instrument approach with nearby obstructions.

Perceived Reliability

A signal is reliable if it consistently performs in the same manner over time. ATC systems are designed so that a signal will always activate if a given threshold is exceeded. Other factors may affect the controller’s perception of a signal’s reliability, however. For example, a snowbank caused by plowing operations has been reported to affect the reliability of an AMASS “Go Around” alert. (Ruskin et al., 2021)

Signal Design Process

This signal framework is intended for either the evaluation of an existing alarm or the design of a new alarm, using an objective scoring sheet and a structured interview with subject matter experts. For each step of the process, a minimum of three air traffic controllers should complete each step so that inter-rater reliability can be measured. The process is as follows:

To Redesign or Evaluate an Existing Signal:

1. Rate the effectiveness of each characteristic for the current signal using the objective scoring sheet. Each characteristic is rated on a scale of 0-5 (0 = poorly designed; 5 = perfectly designed).
2. Choose the three (or more) properties that are most relevant for the current signal.

3. Air traffic controllers (i.e., subject matter experts) participate in a structured interview on the three chosen properties to analyze the qualitative characteristics of the signal. (Tables 2a-n)

4. A prototype signal is designed by human factors experts and system engineers based on the initial scoring and interviews.

5. After a preliminary design is completed, air traffic controllers then use the objective scoring sheet to evaluate each characteristic of the prototype alarm on a scale of 0-5 (0 = poorly designed; 5 = perfectly designed).

6. This process is repeated in an iterative fashion until a satisfactory signal design has been achieved.

To Design a New Signal

1. Rate the importance of each characteristic for proposed signal using the objective scoring sheet. Each characteristic is rated on a scale of 0-5 (0 = Not important at all; 5 = Extremely important).
2. Choose the three (or more) properties that are most relevant for the new signal.

2. Human factors experts conduct a structured interview with air traffic controllers to analyze the qualitative characteristics required for the new signal. (Tables 2a-n)

3. A prototype signal is designed by human factors experts and engineers based on the initial scoring and interviews.

4. Air traffic controllers evaluate the prototype signal using the objective scoring sheet to evaluate each characteristic on a scale of 0-5 (0 = poorly designed; 5 = perfectly designed).

5. This process is repeated in an iterative fashion until a satisfactory signal is achieved.

This framework has both a quantitative and a qualitative component, each of which results in a written record. This provides comprehensive, permanent documentation of the rationale for each design feature. This record can later be referenced to understand the original intentions of the subject matter expert and designer, which may be helpful when updates to a signal are required in response to changes to the equipment or environment.

Figure 1: Alarm Evaluation or Design Process

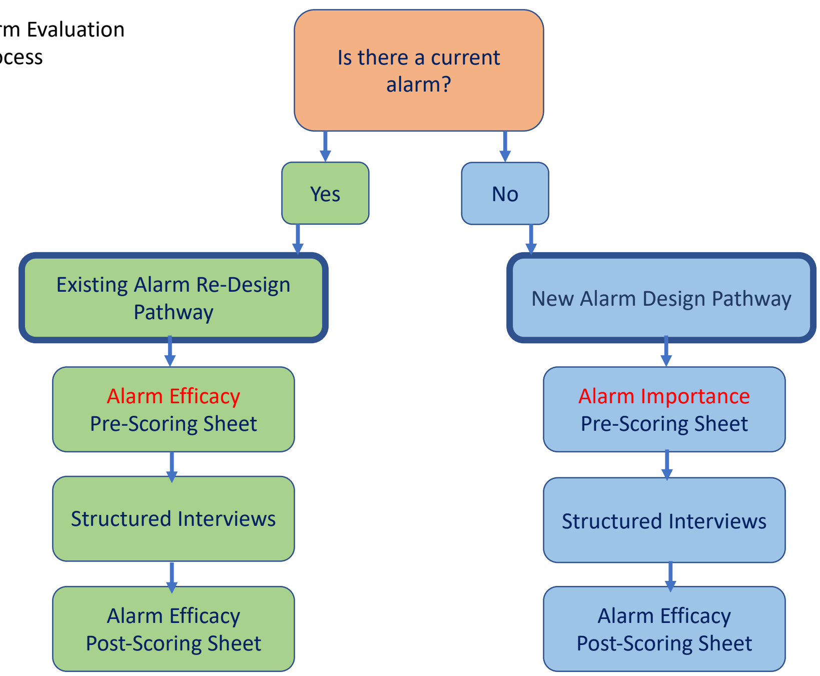

Table 1a: The Framework as Applied to Tower and TRACON Signals

	Factor	Current Air Traffic Control Alarm	Future Possible Improvements
HOW	Modality (Visual, auditory, tactile)	Visual blinking display/ Auditory alert	Add a tactile component
	Priority	No system to suppress lower priority signals	Develop a system to suppress lower-priority signals when specific criteria are met
	Saliency/Noticeability (Contrast, color, size, shape, luminance, timbre, amplitude and frequency, texture, speed/pattern)	Current signals consist of pulsed or alternating tones	Add a speech-based component for time-critical or high-hazard situations
	Disruptiveness	Attracts attention, but is non-specific and frequently sounds at inappropriate times (*e.g.*, during formation flight)	Improve properties of suppressibility, distinguishability, and informativeness
WHAT	Distinguishability	Pulsed tones may be difficult to distinguish from other alarms if the controller's attention is on another part of the display	Each signal should be unique Auditory icons may be helpful for critical signals
	Exclusivity	Each signal is unique to a specific hazard (*e.g.*, MSAW)	Different sounds or signals of other modalities (visual, tactile) for different hazards
	Familiarity Recognizability	The signal is easily recognizable by the controller.	Current signals can easily be recognized by controllers.
	Consistency between systems	Systems vary in their presentation of signals between different facilities and sometimes even in the same facility. (e.g., Two indicators flashing red might mean different things on different systems.)	Consistency in presentation and meaning of signals across various systems and facilities.
	Informativeness	The data block on a TRACON display include CA for conflict alerts, LA for low altitude alerts,	Speech-based signals may enhance a controller's ability to respond to an immediate hazard (e.g., imminent NMAC)

		and MSAW for minimum safe altitude alerts	
WHERE	Location	At controller's workstation	Wearable device with visual, auditory, or tactile components
	Recipient	Heard primarily at the controller's workstation	Signals may need to be received by personnel at multiple locations (*e.g.*, AMASS alarms in an ATCT)
WHEN	Temporality	The signal should activate soon enough that the controller can intervene in a timely fashion	None
	Suppressibility	Can be suppressed under specific circumstances	Reactivation under specific circumstances may be desirable
WHAT	Accuracy	*e.g.*, Inhibit areas configured by local facility	Allowing controllers to adjust the sensitivity of a signal under specific circumstances (*e.g.*, formation flight)
	Reliability		

CATEGORY #1: HOW (How should the alarm notify the air traffic controller?)
MODALITY, PRIORITY, SALIENCY, and DISRUPTIVENESS

1a. ***Modality***. The sensory input used to present an alarm (*e.g.*, visual, auditory, tactile, olfactory or gustatory[7]) determines its *modality*.

Information to Be Collected During Structured Interview	Why Is this Information Important?	Background
What is the dominant sense with which the controller will perceive the alarm?	The optimal sensory modality for an alarm may change depending on the environment and the controller's task load.	An appropriate choice of modality can improve alarm detection (*e.g.*, a tactile stimulus in a loud environment).
What is the current modality for this alarm (for existing alarms).	If the controller has learned to rely on a specific modality and the alarm is	Examples of alarms that work well could include a highlighted visual

Does this modality work well? If it doesn't work well, why?	working well, there may be no need to change the alarm's modality. If the controller has difficulty perceiving the alarm or the environment has changed, a new sensory modality may be necessary.	indicator for a low-priority alarm that does not signal imminent harm or a loud, audible alarm to signal an immediate risk of injury or death in a noisy control tower. Conversely, an audible or tactile alarm for a low-priority event could be unnecessarily distracting.
What modality would be best for this alarm? Would more than one modality for this alarm be beneficial?	The use of multi-modal alarms (e.g., adding visual or tactile components to an auditory alarm) can increase perceived urgency and will increase the rate of compliance with an alarm's signal.	Multi-modal alarms, however, can cause increased workload or distraction if they are not designed and tested for integration (i.e., simultaneous stimulation from the same point of origin).

1b. ***Priority***. Priority refers to which alarm takes precedence. During the structured interview, detailed information should be collected about the priority of the hazard.

Information to Be Collected During Structured Interview	Why Is this Information Important?	Background
What is the priority of the alarm and hazard?	Alarms indicating more critical hazards should receive priority over alarms indicating hazards that can be managed at a later time or hazards that do not present an immediate risk of harm.	For example, most modern automobiles are outfitted with multiple alarms. While alarms for low fuel, open trunk, low tire pressure, and change oil are meant to inform the driver of important hazards, they are not as critical as the alarm for collision avoidance.
What should the priority of the alarm be given the nature of the hazard?		
What is the priority level of the alarm compared to other alarms in that environment?	High-priority alarms should be placed in more easily perceived locations because the a priority location will facilitate the speed of alarm awareness and response.[34]	For example, high-priority visual alarms should be placed directly in front of the controller.

1c. ***Saliency***. *Saliency* refers to the prominence of an item, or “the quality of being particularly noticeable or important”,[17] and indicates how easy it is for a user to notice or detect an alarm. *Saliency* can be indicated by the subfactors of *contrast* (visual, tactile), *color* (visual), *size* (visual, tactile), *shape* (visual, tactile), *luminance* (visual)*, amplitude/volume* (auditory, tactile), *frequency* (auditory), *duty cycle, and pattern* (visual, auditory, tactile).

Information to Be Collected During Structured Interview	Why Is this Information Important?	Background
How easy is it to notice the signal?	Signals of high priority that require an immediate response should have high saliency, while an alarm with low priority may be designed with lower saliency but should still be easily noticeable under low workload conditions.	Low saliency items share common features with their backgrounds and are harder to detect and process, while high saliency items have unique features that stand out from the background.
Should the signal be more noticeable? If yes, what could be done to make it more noticeable?		
In which situations should the alarm be more or less noticeable?		
Is the alarm unnecessarily distracting? If yes, which features contribute to this problem?		
What can be done to optimize the saliency of the alarm?		
What are the potential environmental distractors that can prevent the controller from noticing the alarm?	Higher alarm saliency is needed to attract the attention of the operator in high distraction or cluttered environments.	Potential distractors could include an environment that already has multiple other visual displays. Distractors can also be auditory or tactile. The controller may be distracted by fatigue, emotions, or other recent events.

1d. ***Disruptiveness***. A highly *disruptive* alarm will interfere with the user's attention until the alarm is silenced. It will interfere with other tasks that the controller is doing and will demand that the controller stops their current task to pay attention to the alarm.

Information to Be Collected During Structured Interview	Why Is this Information Important?	Background
Does the intended alarm sufficiently disrupt the clinician's attention?	Emergency alarms should typically be more disruptive than less urgent alerts because they are higher priority and must be addressed immediately.	A highly disruptive alarm can be perceived in the presence of other, distracting stimuli and attract the attention of the operator. For example, a flashing light may not attract the attention of a busy controller, but a loud, auditory alarm will.
Does the intended alarm excessively disrupt the clinician's workflow or cognition?	Alarms should not be so disruptive that the user is overwhelmed with the alarm itself.	The disruptive nature of alarms can grow exponentially when multiple alarms have been activated at the same time, as seen in many ICUs or operating rooms.

CATEGORY #2: WHAT (In what way should the alarm notify the air traffic controller?) DISTINGUISHABILITY, EXCLUSIVITY, FAMILIARITY, and INFORMATIVENESS

2a. ***Distinguishability***. Distinguishability refers to the uniqueness of each alarm when multiple alarms are presenting simultaneously.

Information to Be Collected During Structured Interview	Why Is this Information Important?	Background
How many other alarms may occur in the environment simultaneously?	Visual alarms can be varied in their color, shape, size and illumination; auditory alarms can be varied in their volume, pitch, and timbre. A verbal component may be added; tactile alarms can be varied in their intensity, size, and texture.	A lack of distinguishability has been cited as a reason for poor performance of medical alarms in the intensive care unit and operating room and has been cited in ASRS reports.
How easy is it to tell the alarms apart?		
How often have you mistaken this alarm for a different alarm or hazard?		
How different should this alarm be from other alarms?	In some cases, it is beneficial for all alarms of a certain class to have similar features.	
What can be done to make this alarm more distinguishable from similar alarms?	Icons are one example of a tool to increase distinguishability. Auditory, visual, and tactile features can be varied (see factor: 'saliency')	Visual icons have been used in other domains, such as medicine. Use of auditory icons is a promising modality.

2b. ***Exclusivity***. *Exclusivity* refers to an alarm that is paired to a single hazard.

Information to Be Collected During Structured Interview	Why Is this Information Important?	Background
How many hazards does the current alarm potentially signal?	To eliminate confusion, an alarm should usually be unique for a given hazard.	Tower and TRACON controllers currently experience signals with distinct sounds for CA, MSAW, and AMASS. ARTCC equipment does not currently use audible signals.
How many hazards should a signal be limited to?	Unrelated hazards should not be associated with similar signals.	CA, MSAW, and MCI signals are exclusive. The controller can quickly determine the nature of the hazard by listening to the alarm sound.

2c. ***Familiarity/Recognizability***. A controller who is familiar with the sound, site, or feel of a signal may be more easily able to distinguish it from other alarms.

Information to Be Collected During Structured Interview	Why Is this Information Important?
Is the intended alarm familiar to the controller?	A controller is more likely to respond to an alarm modality that they are familiar with.
If the alarm is not familiar, and this is an important factor, what changes can be made so this alarm will be easier to recognize?	

2d. ***Consistency***. A controller who is familiar with the sound, site, or feel of a signal may be more easily able to distinguish it from other alarms.

Information to Be Collected During Structured Interview	Why Is this Information Important?
Is the intended alarm consistent with similar signals used on other equipment?	A controller is more likely to respond to an alarm modality that is consistent with others that they have learned. Consistency may also reduce cognitive workload.
If the alarm is not consistent, is there an important design consideration that outweighs this factor?	

2e. ***Informativeness***. Informativeness refers to the alarm providing only the information needed for the clinician to manage the hazard while avoiding alarm flood (overwhelming the user with irrelevant data or too many alarms at once).

Information to Be Collected During Structured Interview	Why Is this Information Important?
Does the current alarm provide enough information about the hazard?	The user may not have time to process large quantities of information, particularly during a critical event. Signals should therefore provide actionable information, especially when a hazard is urgent. Signals associated with a less urgent event may be designed to provide more information.
What changes can be made to increase the informativeness of the alarm?	
Does the signal provide information about the time remaining to resolve the hazard? Should it provide this information?	
Does the signal provide an indication or deactivate when the hazard has been resolved?	

CATEGORY #3: WHERE (Where should the notification of the air traffic controller occur?) LOCATION and RECIPIENT

3a. ***Location***. Location describes where the alarm is physically placed.

Information to Be Collected During Structured Interview	Why Is this Information Important?	Background
Where is the location of the alarm now (for existing alarms)? Is the current location the best location for that alarm? If not, what location would work better? What is the ideal location (for a new alarm)?	The location of the alarm should optimize clinician detection without causing undue distraction.	For example, a tactile alarm located on a vest can be strategically located to help the operator determine where to direct their attention. Sometimes alarms for related hazards are in disparate locations. For example, a CA and AMASS signals may be located in different areas of a control tower, increasing the difficulty of integrating the information conveyed by alarms on each device.
Should the alarm indicate the location of the hazard? Will the location of the hazard change over time?	Multiple auditory alarms in different locations may help a controller to determine where the hazard is occurring.	Humans can typically detect differences in auditory locations. The location of an alarm may be facilitated by using lower frequencies (*i.e.*, less than approximately 800 Hz) because

		inter-aural differences are used to localize sound.

3b. ***Recipient***. *Recipient* refers to the controllers(s) who need to be aware of the alarm.

Information to Be Collected During Structured Interview	Why Is this Information Important?
Who is (are) the intended recipient(s) of the alarm?	The alarm should be easily perceived by the intended recipients. For example, a controller working at a radar facility needs to be aware of the signals that appear at his or her station. A tower environment may have more than one controller or a single controller who must move between several locations in the cab.
Are there multiple intended recipients for the alarm?	Designers should ensure that the alarm will effectively reach all intended recipients. *E.g.*, multiple personnel in a control tower
Will the intended recipient's location change?	If the recipient is in a single location, the signal can be in that location. If, however, the recipient must move between locations, the alarm should be designed to move with the recipient.
Is there a potential for the recipient's vision to be limited? [20]	A limited visual field may decrease the controller's ability to perceive some visual alarms.
Do any of the intended recipients have impairments or disabilities that may interfere with their perception of the signal?	The signal designer should consider the possibility that the controller could have a physical disability (e.g., color vision deficiency) or other impairment that could interfere with the perception of the alarm.

CATEGORY #4: WHEN (When should the alarm notify and stop notifying the air traffic controller)
TEMPORALITY and SUPPRESSIBILITY

4a. ***Temporality***. The *temporality* of the alarm determines when the alarm will be activated, how long the alarm will be activated for, and when the alarm stops.

<table>
<tr><td>Information to Be Collected During Structured Interview</td><td>Why Is this Information Important?</td><td>Background</td></tr>
<tr><td>How soon after the onset of the hazard should the controller be warned?</td><td rowspan="2">In some situations, it may be desirable for the alarm to sound immediately, such as to alert the clinician to asystole. In some cases, designers should build in a delay. For example, for lower priority hazards, a delayed alarm will give clinicians a chance to resolve the hazard on their own (and decrease alarm fatigue).</td><td rowspan="2"></td></tr>
<tr><td>Does the current alarm stay activated for the appropriate period of time?</td></tr>
<tr><td>What are the indicators that the hazard is no longer ongoing? Does the current alarm deactivate in the correct time frame after the hazard is resolved?</td><td>If an alarm is deactivated too quickly, a controller may prematurely believe that the hazard has been resolved.</td><td>For example, if a fire alarm is silenced, people may think they no longer need to evacuate</td></tr>
<tr><td>What is the urgency of the hazard? [13,32]</td><td>Auditory alarms may be more effective in communicating urgency than visual alarms.</td><td>An individuals’ field of audibility is greater than an individuals’ field of view</td></tr>
<tr><td>Could the urgency level of the hazard change?</td><td>There may be a need to update the urgency conveyed by the alarm and/or add alarm modalities as the hazard progresses.</td><td>For example, the pilot of an aircraft that generated an MSAW may agree to turn away from rising terrain. If the pilot continues toward the hazard, however, a high priority alarm may be required if CFIT is imminent.</td></tr>
</table>

4b. ***Suppressibility***. *Suppressibility* refers to how much control the controller has over inhibiting the alarm. Joint Order 7110.65 offers specific guidance on when a controller can suppress or deactivate a signal.

<table>
<tr><td>Information to Be Collected During Structured Interview</td><td>Why Is this Information Important?</td><td>Background</td></tr>
<tr><td>How can the signal be suppressed?</td><td rowspan="2">Some signals cannot be suppressed while some can be dimmed, delayed, muted, or disabled by the controller.</td><td rowspan="2">Some signals should not be suppressible. When alarm designers decide to allow suppressibility, they should consider 1) the level of the hazard, 2) how much time the controller should be given to resolve the hazard, and 3) what criteria should reactivate the signal. Alarm designers should also consider the distractibility of the signal. In some cases, the signal should be allowed to activate once and then immediately become silent—or be disabled—to reduce distractions.</td></tr>
<tr><td>What are the advantages and disadvantages of suppressibility for this alarm?</td></tr>
<tr><td>What are some unauthorized ways of deactivating the alarm?</td><td>Visual alarms that are designed to prevent deactivation or muting can easily be suppressed by the user by covering the output with a piece of tape. Suppressing alarms in a manner that is not consistent with equipment design can have life-threatening consequences.</td><td>In one study, almost 59% of alarms in an intensive care unit had either been deactivated or “personalized” by resetting limits.[16]</td></tr>
</table>

CATEGORY #5: WHY (What should the alarm indicate about the hazard?)
PERCEIVED ACCURACY AND PERCEIVED RELIABILITY

5a. ***Perceived Accuracy***. Accuracy refers to the avoidance of false alarms and misses. False alarms occur in the absence of a hazard, while misses fail to detect the hazard. Consider, for example, a smoke detector that has been installed for 1000 days. During this time, the detector correctly stays quiet for 999 days when there is no smoke. When there is smoke, the detector fails to alarm, and a fire ensues. This detector is 99.9% accurate, even though it failed at a critical time. The obvious question is how often the smoke detector is activated when there is smoke. According to SDT, *sensitivity* indicates how successful an alarm is at completing its task when controlling for designer bias. *Designer bias* describes whether the detector has been programmed to be biased towards avoiding misses (resulting in more false alarms) or avoiding false alarms (resulting in more missed events).

Information to Be Collected During Structured Interview	Why Is this Information Important?	Background
What factors will impair alarm accuracy, by causing a false alarm or conversely, a miss?	False alarms will increase workload unnecessarily. Both false alarms and misses can have a detrimental effect on long-term trust in the alarm.	False alarms can lead to alarm fatigue, which has often been cited as a reason for suppressing alarms.
What modifications to the alarm can help to minimize false alarms and misses?	Alarm designers could allow for automatic and clinician-set modifications to the alarms' sensitivity and specificity to fit the clinical situation.	Alarm modifications could include inhibit areas and automatic transient deactivation under specific circumstances (e.g., if the controller indicates that a group of airplanes is a formation flight).
How do false alarms and misses affect performance?	If the user does not trust the alarm because of excessive false alarms or misses, they may ignore it or turn it off.	Controllers may disregard a signal that is activated but requires no action. (e.g., a CA that activates during simultaneous close parallel approaches)

5b. ***Perceived Reliability***. An alarm is *reliable* if it consistently performs in the same manner over time.

Information to Be Collected During Structured Interview	Why Is this Information Important?	Background
How reliable is the current alarm?	A reliable alarm always indicates the presence of a hazard.	An alarm that is inconsistent is not accurate.
How reliable does the alarm need to be?	Less reliability could be acceptable for alarms indicating less important hazards.	For an alarm indicating a less important hazard, designers may accept less reliability to prioritize other goals.
Which indicators of the hazard are most consistent?	The most consistent indicators of the hazard will determine the cues that will be used to activate the alarm	

Chapter 5: Conclusions

The National Airspace System in which air traffic controllers work is a complex and demanding environment that requires vigilance and frequent multitasking. ATC systems employ a high level of automation, using various algorithms to detect runway incursions, conflicts, and altitude deviations. Although the automation is designed to help controllers perform their job safely and effectively, imperfect automation with suboptimal signaling systems can degrade performance. Effective signals are therefore essential to aviation safety, and the roadmap that we describe in this handbook can be used to enhance their utility. To facilitate the signal design process, we have developed a framework that links users' needs to alarm design by specifying a common language that can be used by subject matter experts, human factors experts, and equipment designers. This handbook, along with the FAA's Human Factors Design Standard (Ahlstrom and Longo, 2003), will provide equipment designers with guidance to help them develop signals that controllers will use to keep the National Airspace System the safest in the world. Although the process described in this handbook focuses on the design and implementation of signals in the setting of air traffic control, we believe that the framework that we developed has broad applicability across multiple domains.

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Appendix A: Potential Signal Enhancements

<u>Currently used in ATC</u>

- Pulsed auditory signals
- Verbal instructions (*e.g.*, ASDE-X "Go around!")
- Visual signals, including color

<u>Currently used in aviation</u>

- Tactile signals (stick shaker)
- Increasing size of critical information
- Simplifying display to highlight critical information

<u>Used in industries other than aviation (*e.g.*, manufacturing)</u>

- Vibrotactile signals
- "Time to go" indicators (*e.g.*, moving bar)
- Color-coded and shape coded visual indicators
- Earcons

<u>Possible future applications: additional research required</u>

- Spearcons
- Sound characteristics to encode urgency
    - Timbre
    - Chords
    - Contour
- Directional signals
    - Incorporating noise into pure tones
    - Highly directional loudspeakers

Appendix B: Signal Design Process

This signal framework is intended for either the evaluation of an existing alarm or the design of a new alarm, using an objective scoring sheet and a structured interview with subject matter experts. The framework includes physical factors (modality, location, exclusivity, and suppressibility), psychological factors (salience, heterogeneity, informativeness, and disruptiveness), and performance-related factors (recipient, accuracy, reliability, priority, and temporality). The signal framework has both a quantitative and a qualitative component, each of which produces a written record. This provides comprehensive, permanent documentation of the rationale for each design feature. This record can later be referenced to understand the original intentions of the subject matter expert and designer, which may be helpful when updates to a signal are required in response to changes to the equipment or environment.

For each step of the process, a minimum of three air traffic controllers should complete each step so that inter-rater reliability can be measured. The process is as follows:

To Redesign or Evaluate an Existing Signal:

1. Air traffic controllers (i.e., subject matter experts) first rate the effectiveness of each characteristic for the current signal using the objective scoring sheet. Each characteristic is rated on a scale of 0-5 (0 = poorly designed; 5 = perfectly designed).

2. Controllers then participate in a structured interview to analyze the qualitative characteristics of the signal. The controllers' responses are transcribed to create a permanent record. The structured interview script is in the next section. Several options are given in the instructions for the participant, depending on whether the interview is being used to design a new signal or to evaluate an existing signal.

3. A prototype signal is designed by human factors experts and system engineers based on information gathered during the initial scoring and interviews.

4. After a preliminary design is completed, air traffic controllers then use the objective scoring sheet to evaluate each characteristic of the prototype alarm on a scale of 0-5 (0 = poorly designed; 5 = perfectly designed).

5. This process is repeated in an iterative fashion until a satisfactory signal design has been achieved.

To Design a New Signal

1. Air traffic controllers first rate the importance of each characteristic for proposed signal using the objective scoring sheet. Each characteristic is rated on a scale of 0-5 (0 = Not important at all; 5 = Extremely important)

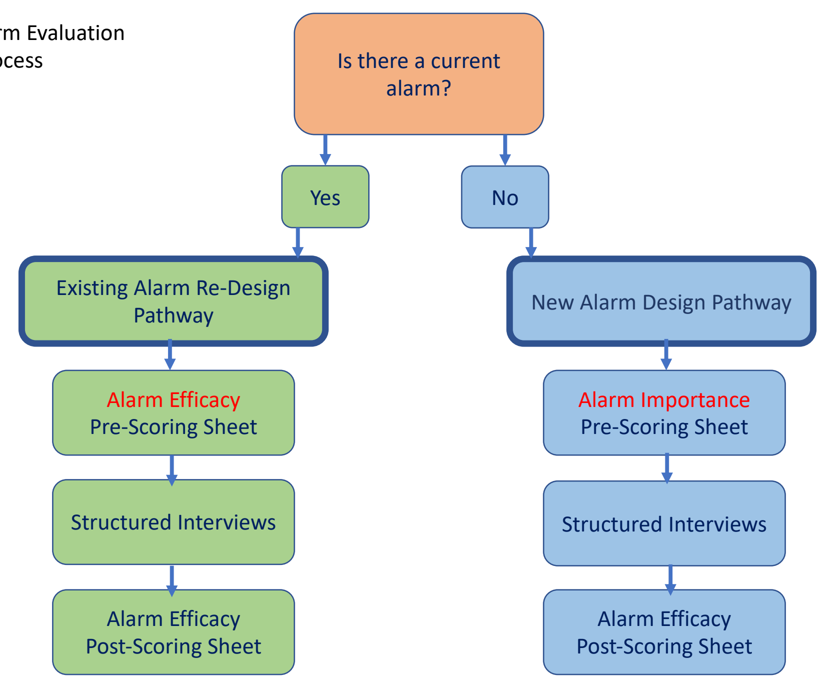
2. Human factors experts conduct a structured interview with air traffic controllers to analyze the qualitative characteristics required for the new signal. Responses to the structured interview are transcribed to create a permanent record.

3. A prototype signal is designed by human factors experts and engineers based on the initial scoring and interviews.

4. Air traffic controllers evaluate the prototype signal using the objective scoring sheet to evaluate each characteristic on a scale of 0-5 (0 = poorly designed; 5 = perfectly designed).

5. This process is repeated in an iterative fashion until a satisfactory signal is achieved.

Figure 1: Alarm Evaluation or Design Process



Structured Interview Script

Controller position ______

Time at current position ______

Previous positions _____

Time at previous positions ______

Previous experience with operations and automated systems that provide alerts and/or alarms ______

The purpose of this interview is to seek your opinions on hazards and alarm (used at your facility / being proposed as a new alarm / to be developed as a new alarm). We will do this by taking you through an example structured interview, asking your opinion on what is important for this alarm. We will be asking you to rate the importance of this alarm overall, then to answer questions about a number of properties related to alarms, and to rate each property. For the ratings, we will be using a Likert scale of 1 to 5, with 1 = not at all important and 5 = very important

Overall: How important is having an alarm for __________ in the air traffic control environment? – **Likert overall** =

CATEGORY #1: HOW (How should the alarm notify the controller?)
PRIORITY, SALIENCY, and DISRUPTIVENESS

1a) PRIORITY. *Priority* refers to which alarm takes precedence. The order of priorities is: Alarm (immediate action is required), Alert (action may be required in the future), and Warning (a continuously present hazard). Although we will be using these terms, the naming convention of aural notifications has not been consistent. For example, an imminent conflict alert is really an alarm because the controller needs to take immediate action. In en route environment, Conflict Probe Alert indicates a possible airspace incursion that could be as far in the future as 40 minutes. Alarms indicating more critical hazards should receive priority over alarms indicating hazards that can be managed at a later time or hazards that do not present an immediate risk of harm. For example, most modern automobiles are outfitted with multiple alarms. While alarms for low fuel, open trunk, low tire pressure, and change oil are meant to inform the driver of important hazards, they are not as critical as the alarm for collision avoidance, which is more noticeable. High-priority alarms should be placed in more easily perceived locations because the location will facilitate the speed of alarm awareness and response. For example, high-priority visual alarms should be placed directly in front of the air traffic controller. Some of the variables that can be manipulated for priority include the time available to respond to the hazard, sequencing (higher priority alarm alerts you first), and layering (higher priority alarm on top on a visual computer screen).

What do you think about the current alarm priority at your current position? Are there examples of the current priority working well? Not well?

Questions about the __________ alarm:

What should the priority level of the alarm be compared to other alarms in the environment?

Likert for importance of priority =

1b) SALIENCY. *Saliency* refers to the prominence of an item, or "the quality of being particularly noticeable or important," and indicates how easy it is for a user to notice or detect an alarm. *Saliency* can be indicated by the subfactors of *contrast* (visual, tactile), *color* (visual), *size* (visual, tactile), *shape* (visual, tactile), *luminance* (visual)*, amplitude/volume* (auditory, tactile), *frequency* (auditory), *texture* (tactile), *speed, pattern, and length* (visual, auditory, tactile). Higher alarm saliency is needed to attract the attention of the operator in high distraction or cluttered environments.

What do you think about the current alarm saliency at your current position? Are there examples of the current saliency working well? Not well?

Questions about the __________ alarm:

How easy should it be to notice the alarm?

What can be done to make the alarm more noticeable?

In which situations do you need the alarm to be more noticeable?

In which situations do you need the alarm to be less noticeable?

Which factors (contrast, color, size, shape, luminance, volume, frequency, texture, speed, pattern, length) should be used to help the user notice this alarm? Which factors would be unnecessarily distracting?

What are the potential distractors *in the environment* that can prevent the air traffic controller from noticing the alarm?

Likert for importance of salience =

1c) DISRUPTIVENESS A highly *disruptive* alarm will interfere with the user's attention until the alarm is silenced. It will interfere with other tasks that the air traffic controller is doing and will demand that the air traffic controller stops their current task to pay attention to the alarm. Emergency alarms should typically be more disruptive than less urgent alerts because they are higher priority and must be addressed immediately. A highly disruptive alarm can be perceived in the presence of other, distracting stimuli and attract the attention of the air traffic controller. For example, a flashing light may not attract the attention of a busy air traffic controller, but a loud, auditory alarm will. Alarms should not be so disruptive that the user is overwhelmed with the alarm itself. The disruptive nature of alarms can grow exponentially when multiple alarms have been activated at the same time, as seen in many ICUs or operating rooms. Some of the variables that can be manipulated for disruptiveness include intrusiveness and saliency.

What do you think about the current alarm disruptiveness at your current position? Are there examples of the current level of disruptiveness working well? Not well?

Questions about the __________ alarm:

How much should the alarm disrupt the air traffic controller's attention?

How can the alarm avoid excessively disrupting the air traffic controller's workflow and cognition?

Likert for importance of disruptiveness =

CATEGORY #2: WHAT (In what way should the alarm notify the controller?) MODALITY, DISTINGUISHABILITY, EXCLUSIVITY, FAMILIARITY, and INFORMATIVENESS

2a) MODALITY The sensory input used to present an alarm (*e.g.*, visual, auditory, tactile, olfactory or gustatory[7]) determines its *modality*. For example, a tactile component to an alarm can help in a loud environment, such as a steering wheel that vibrates when a vehicle deviates from a lane during travel. Another example is the odor of natural gas (from added mercaptans), serving as a passive alarm that is immediately detectable. Loud alarms may work well for high-priority events but could be unnecessarily distracting for a low-priority event.

What do you think about the current alarm modalities used at your current position? Are there examples of the current modalities working well? Not well?

Questions about the __________ alarm:

What modality would be best for this alarm? (What is the dominant sense with which the air traffic controller will perceive the alarm?)

What other modalities should be used for this alarm? (What other senses will the air traffic controller also use to perceive the alarm?)

Would more than one modality for this alarm be beneficial?

Could some modalities be unnecessarily distracting? When? Why?

Likert for importance of modality =

2b) DISTINGUISHABILITY

Distinguishability refers to the uniqueness of each alarm when multiple alarms are presented simultaneously. If you have multiple alarms activated at the same time, can you tell which is which? If you have 2 verbal alarms, low distinguishability would mean that you can't easily tell them apart. An example of better distinguishability would be for the higher priority alarm at that moment to have both a verbal and a tonal component and the lower priority alarm to have only a tonal component.

Visual alarms can be varied in their color, shape, size and illumination; auditory alarms can be varied in their volume, pitch, and timbre. A verbal component may be added; tactile alarms can be varied in their intensity, size, and texture. In some cases, it is beneficial for all alarms of a certain class to have similar features. Some of the variables that can be manipulated for distinguishability include heterogeneity, identifiability, uniqueness, diversity, and variety.

What do you think about the current alarm distinguishability at your current position? Are there examples of the current distinguishability working well? Not well?

Questions about the __________ *alarm:*

How different should this alarm be from other alarms?

What can be done to make this alarm more distinguishable from similar alarms?

How many other alarms may occur in the environment simultaneously?

Likert for importance of distinguishability =

2c) EXCLUSIVITY *Exclusivity* refers to a single, discrete alarm being paired to a single, specific hazard. An example of an exclusive alarm is a fire alarm. A fire alarm has one purpose: it only indicates the presence of smoke or fire. The only correct response to a fire alarm is to leave the area. In contrast, the sound used by a microwave oven is non-exclusive. A microwave oven has a single auditory output that could mean multiple things (for example that the user has started the microwave or that the microwave has finished heating the food). If you have multiple similar hazards then you might benefit from the alarm being assigned to a category of hazards, rather than exclusive.

What do you think about the exclusivity of the alarms used at your current position? Are there examples of the current exclusivity working well? Not well?

Questions about the __________ alarm:

How many hazards should the alarm be limited to?

Likert for importance of exclusivity =

2d) FAMILIARITY/RECOGNIZABILITY An air traffic controller who is familiar with the sound, site, or feel of an alarm, may be more easily able to distinguish it from other alarms. An air traffic controller is more likely to respond to an alarm modality with which he or she is familiar. Some of the variables that can be manipulated for familiarity include training and experience.

What do you think about the current alarm familiarity at your current position? Are there examples of the current level of familiarity working well? Not well?

Questions about the __________ alarm:

How familiar would the alarm be to the air traffic controller?

What can be done to make this alarm easy to recognize?

Likert for importance of familiarity/recognizability =

2e) CONSISTENCY A controller is more likely to respond to signal that is *consistent* between facilities and types of automation within a given facility. Consistency may also reduce cognitive workload.

Questions about the __________ alarm:

Is the intended alarm consistent with similar signals used on other equipment? Are there examples of the current level of consistency working well? Not well?

If the alarm is not consistent between different types of equipment, is there an important design consideration that outweighs this factor?

Is there anything that could be done to improve consistency of this alarm between different types of equipment?

Likert for importance of consistency =

2f) INFORMATIVENESS *Informativeness* refers to the alarm providing only the information needed for the air traffic controller to manage the hazard while avoiding *alarm flood* (overwhelming the user with irrelevant data or too many alarms at once). In other words, with an informative alarm, the air traffic controller will know what to do when they hear the alarm. The verbal alarm on an AMASS is a good example of an informative alarm, it states the problem and tells the controller what to do. The user may not have time to process an avalanche of raw data, particularly during a critical event. Alarms must therefore immediately provide actionable information. Less urgent alerts may be designed to provide more information, depending on how much time the user has to process this information before a response is required. Some of the variables that can be manipulated for informativeness include relevance, directiveness, urgency, and training.

What do you think about the current alarm informativeness at your current position? Are there examples of the current informativeness working well? Not well?

Questions about the __________ alarm:

How much information should the alarm provide?

How much information should the alarm provide about the time remaining to resolve the hazard?

Should the alarm provide an indicator or cease when the hazard has been resolved?

Likert for importance of informativeness =

CATEGORY #3: WHERE (where should the notification of the controller occur)
LOCATION and RECIPIENT

3a) LOCATION. Location describes where the alarm is physically placed. The location of the alarm should optimize air traffic controller detection of the alarm without causing undue distraction. For example, a tactile alarm located on a vest or headband can be strategically located to help the operator determine where to direct their attention, although there is potential for this to be distracting. Some of the variables that can be manipulated for location are distance of the alarm and direction of the alarm from the controller.

What do you think about the current alarm locations at your current position? Are there examples of the current locations working well? Not well?

Questions about the __________ alarm:

What is the ideal location for this alarm?

What kind of potential exists for this alarm location to be distracting?

Should the alarm itself indicate the location of the hazard?

Will the location of the hazard change over time?

Likert for importance of location =

3b) RECIPIENT *Recipient* refers to the air traffic controller(s) who need to be aware of the alarm. If the recipient is in a single location, the alarm can be in that location. If, however, the recipient must move between locations, the alarm should be designed to move with the recipient. An air traffic control tower that it brightly lit by sunlight may impair a controller's ability to perceive a blinking light. The alarm designer should consider the possibility that the air traffic controller could have a physical disability or impairment (e.g., color blindness) that could interfere with the perception of the alarm. Some of the variables that can be manipulated for recipient include number of recipients, scope, and required action.

What do you think about the current alarm recipients at your current position? Are there examples of the current intention for alarm recipients working well? Not well?

Questions about the __________ alarm:

Who are the intended recipient(s) of the alarm?

Are there multiple intended recipients for the alarm? If yes, who?

Will the intended recipient's location be dynamic?

Is there a potential for the recipient's vision or other senses to be limited?

Do any of the intended recipients have impairments or disabilities that may interfere with their perception of the alarm?

Likert for importance of recipient =

CATEGORY #4: WHEN (when should the alarm notify and stop notifying the controller) TEMPORALITY and SUPPRESSIBILITY

4a) TEMPORALITY The *temporality* of the alarm determines when the alarm will be activated, how long the alarm will be activated for, and when the alarm stops. In some situations, it may be desirable for the alarm to sound immediately, such as to alert the air traffic controller to loss of separation. In some cases, designers should build in a delay. For example, for lower priority hazards, a delayed alarm will give air traffic controllers a chance to resolve the hazard before the alarm is activated (potentially decreasing alarm fatigue). Some of the variables that can be manipulated for temporality include start time, stop time, and immediacy.

What do you think about the current alarm temporality at your current position? Are there examples of the current temporality working well? Not well?

Questions about the __________ alarm:

How soon after the onset of the hazard should the air traffic controller be warned?

Should the alarm continue to sound throughout the hazard, or should it stop automatically before the hazard is resolved?

Could the urgency level of the hazard change?

Likert for importance of temporality =

4b) SUPPRESSIBILITY. *Suppressibility* refers to how much control the air traffic controller has over inhibiting the alarm (either manually when the alarm occurs, or by setting the parameters for an 'automatic suppression'. Some alarms cannot be suppressed. Some alarms can be dimmed, delayed, muted, or disabled by the air traffic controller. Some of the variables that can be manipulated for suppressibility include persistence and required intervention.

What do you think about the suppressibility features of the alarms at your current position? Are there examples of the current suppressibility features working well? Not well?

Questions about the __________ alarm:

Who should be able to suppress the alarm?

How should the alarm be suppressed?

What are the advantages of suppressibility for this alarm?

What are the disadvantages of suppressibility for this alarm?

Likert for importance of suppressibility =

CATEGORY #5: WHAT (What should the alarm indicate about the hazard?)
PERCEIVED ACCURACY AND PERCEIVED RELIABILITY
Note: Cannot change the algorithm that activates the alarm with this project; however, can change alarm characteristics

5A) PERCEIVED ACCURACY Accuracy refers to the avoidance of false alarms and misses. False alarms occur in the absence of a hazard, while misses fail to detect the hazard. False alarms will increase workload unnecessarily. Both false alarms and misses can have a detrimental effect on long-term trust in the alarm. False alarms can lead to alarm fatigue, which has often been cited as a reason for suppressing alarms. Alarm designers could allow for automatic and air traffic controller-set modifications to the alarms' sensitivity and specificity to fit the situation.

Variables that can be manipulated for perceived accuracy:

Variable	Initially determined by the algorithm?	How it could be modified locally by second level engineering	Example
Sensitivity criteria	✓	Inhibit areas	The TRACON could create an inhibit area containing the VFR aircraft that would prevent a MSAW from sounding in the inhibit area. E.g. on a visual hold in Honolulu with the MSAW activated by mountains, ATC could set up an inhibit area saying the signal should not alert unless the distance becomes closer*
Variable probability of hazard	✓	Likelihood indicator	Two aircraft approaching head-on that are about to turn to their final approach courses will trigger the CA, but there is a low likelihood of loss of separation
Confidence that hazard will occur	✓	Time-to-go Bar (potential future feature)	A conflict probe, which can occur up to 40 minutes in the future, could potentially tell you how long before loss of separation will actually occur with a 'time-to-go' bar
Controller judgement that	✗	J-ring	Signal will alert if hazard enters the ring

aircraft may lose separation			

*The system keeps track of if the alarm 'would have' been set off, and 20% of the incidences of if the alarm 'would have' been set off are evaluated regularly

What do you think about the current alarm accuracy at your current position? Are there examples of the current accuracy working well? Not well?

Questions about the __________ *alarm:*

What factors will impair alarm accuracy, by causing a false alarm or conversely, a miss?

What modifications to the alarm can help to minimize false alarms and misses?

Likert for importance of accuracy =

5B) PERCEIVED RELIABILITY

An alarm is *reliable* if it consistently performs in the same manner over time. An alarm that performs well under some circumstances but not others is not reliable (i.e. a change in accuracy over time = unreliable). The variable that can be manipulated for perceived reliability is consistency. For example, AMASS can be affected by snow drifts near a runway, making it inconsistent/less reliable. Future hardware or software improvements might be able to mitigate this effect.

What do you think about the current alarm reliability at your current position? Are there examples of the current reliability working well? Not well?

Questions about the __________ *alarm:*

How reliable does the alarm need to be?

Likert for importance of reliability =

After the structured interview, the human factors expert highlights the signal properties that are most important to the controllers. This information is then provided, along with the transcript of the structured interview, to signal designers. An example brief might read as follows:

ARTCC controllers interviewed for this signal have an average time on position of 12 years. Two had previously worked as local (Tower) controllers and one worked at a different ARTCC prior to moving to the currently facility. All have extensive prior experience with operations and automated systems that interact with controllers who use signals.

All controllers felt that signaling a CA with an alarm was important (Average Likert score 4.5). The current alarm did not indicate a high enough priority for the potential hazard that it represented (Likert 5.0) and they indicated that it should be a higher priority. Because they receive these signals while seated at their workstation, they did not feel that specifying the location of the signal was important. (Likert 1.5.) The only necessary recipient is the controller immediately responsible for the involved aircraft, so location was not an important characteristic of this signal. (Likert 1.0.)

Three controllers stated that a flashing data block did not give them enough time to notice and resolve a problem and asked for additional modalities. They stated that the alarm could attract their attention more effectively by including a tone and a flashing data block. All controllers agreed that an audible alarm would be sufficiently disruptive to attract their attention, especially since audible alarms are not currently used in ARTCCs. (Likert 4.0) Although there are currently no audible alarms used in the en route environment, the controllers stated that a tone could be used to indicate an imminent loss of separation. One suggested that the flash rate of the data block could increase to indicate urgency. One controller reported missing a potential loss of separation during a relief briefing.

The controllers that we interviewed felt that the CA should be highly distinguishable. In the setting of two alarms at once, the CA might better be identified as the more important alarm by including both a verbal and a tonal component while a lower priority alarm might have only a tonal component. The data blocks associated with aircraft that might lose separation could better be identified by changing their color, shape, size, or brightness. Because they both identify similar hazards, proximity alarms and CAs could have similar characteristics, at least in their *initial presentation. Some controllers also felt that any new signals should have audio characteristics that are similar to the current alarm, so as to maintain recognizability. They stated a preference for alarms that sound like ones that they had trained with and encountered in their current environment. (Likert for familiarity 3.5.) Two controllers asked for a verbal component to alert them to a potential hazard while they are looking away from their radar scope or are on the landline. (Likert 3.0) They stated that a loud "Imminent Near Miss! N12345 and Airline 678!) might help them to recognize a critical event sooner. (Likert 4.0.)*

Controllers that we interviewed felt that the CA alarm is critically important and should activate as soon as a possible loss of separation is predicted so that timely action can be taken. (Likert 5.0) In contrast, a signal generated by the conflict probe should build in a delay because it is a lower priority hazard that may occur in the future. Delaying this alarm will give air traffic controllers a chance to resolve the problem before the alarm is activated, potentially decreasing alarm fatigue. Some of the variables that can be manipulated for temporality include start time, stop time, and immediacy. Controllers felt that the CA alarm should be suppressible once it has been acknowledged but should reactivate if the aircraft continue to lose separation. (Likert 4.0.)

After the alarm has been designed, the same structured interview can be used to evaluate a prototype. The transcript from that structured interview and a summary report can then be returned to the equipment designer to further refine the signal. At the end of this process, the series of transcripts and reports provide a permanent, written record of how and why the signal was designed the way that it was. This information can then be used to guide the design of future signals for new hazards or to guide the redesign (if necessary) of signals that have already been implemented.

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